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STUDY AND EVALUATION
OF
FERRO-CEMENT
FOR USE IN
WIND TUNNEL CONSTRUCTION

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FOREWARD

The successful completion of a state-of-the-art survey such as the one reported herein is dependent on the cooperation of a number of individuals. Professor R. B. Williamson, University of California, Berkeley was especially helpful as was Professor S. P. Shah, University of Illinois at Chicago Circle. The assistance of those in industry such as M. E. Irons of Fibersteel Corporation and D. A. Seymour, Naval Architect is also appreciated. Professor W. J. Venuti, California State University, San Jose helped develop the laboratory test criteria and supervised the testing of all samples.

The work in the Blume office was conducted under the general supervision of Roland L. Sharpe, Principal-in-charge, and James E. Boyd, Project Manager. Henry J. Larsen, Jr. was the principal investigator responsible for compilation, review and evaluation of the data as well as planning and conduct of the laboratory testing program.

STUDY AND EVALUATION
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I. INTRODUCTION

This report presents the results of an investigation into the structural suitability and cost effectiveness of ferro-cement for large subsonic wind tunnel structures. It was conducted in accordance with change Item No. 7, dated January 20, 1972, of contract NAS2-5889, dated March 31, 1970. This investigation was carried out in the following four main categories: (1) A state-of-the-art survey into the uses, properties, and costs of ferro-cement; (2) An evaluation of those ferro-cement properties critical to construction of large, subsonic wind tunnels, which have not been adequately established to date; (3) A laboratory testing program to determine preliminary values for those properties; and (4) A study to establish cost factors for ferro-cement as related to a preliminary construction scheme for a nacelle and shroud unit of the type and configuration presented in the March 22, 1971, John A. Blume & Associates, Engineers report, "Conceptual Design Study of Power Section for a Proposed V/STOL Wind Tunnel." These cost data were then used to revise and update the cost estimate in that report pertaining to the use of ferro-cement.

During the course of this investigation published data on ferro-cement research were reviewed and evaluated and recognized experts in ferro-cement research, construction, and economics were consulted. These consultants included university faculty members and government personnel involved in basic research in ferro-cement and also private firms currently engaged in commercial design and construction of ferro-cement marine craft and other structures. Ferro-cement specimens for the laboratory testing program were fabricated at a commercial marine construction yard specializing in ferro-cement boat construction. The specimens were tested at a university testing laboratory experienced in static and fatigue testing of construction materials.

The most significant findings reported herein, relative to wind tunnel construction, are the following:

1. Ferro-cement is a relatively new construction material that consists basically of a thin-shell of Portland cement mortar heavily reinforced with light gage steel wire mesh. Significant improvement in both cracking strength of mortar and the extent of cracking result from wide dispersal of reinforcement in the cross section. Ferro-cement capacity to resist all types of loads except compression is dependent on the volume and surface area of the reinforcement.
2. Surface smoothness and overall durability of ferro-cement is high although protective coatings may be required in corrosive environments. Resistance to impact loads is relatively low. Repair of damaged areas, however, is relatively simple.
3. Estimates based on the properties of dense concrete indicate that the acoustical attenuation properties of a ferro-cement shell are superior to an equivalent steel shell for certain sound frequency ranges.
4. A limited ferro-cement testing program yielded the following results based on the samples tested: (a) Resistance to fatigue loading near the level of cracking stress is high; (b) Resistance to surface abrasion from high velocity air flow is high; and (c) Natural vibration frequencies can be predicted from basic material properties of ferro-cement.
5. In terms of structural and economic feasibility, ferro-cement is most applicable to wind tunnel structures in areas of curved, thin-shell construction with relatively low design loading.

6. For many structures where ferro-cement strength properties are consistent with design requirements, significant cost advantages can be expected relative to structural steel. Maximum economy can be obtained by reducing the large labor costs typical of ferro-cement construction through use of automated production methods.
7. There is a limited amount of ferro-cement test data available at present, relative to other building materials such as steel or concrete. Large-scale structural applications should, therefore, be based on specific test programs to establish an optimum design. Principal areas for further work include more comprehensive fatigue testing, reinforcement and mix design studies, durability studies, and full-scale load testing.

II. THE NATURE OF FERRO-CEMENT

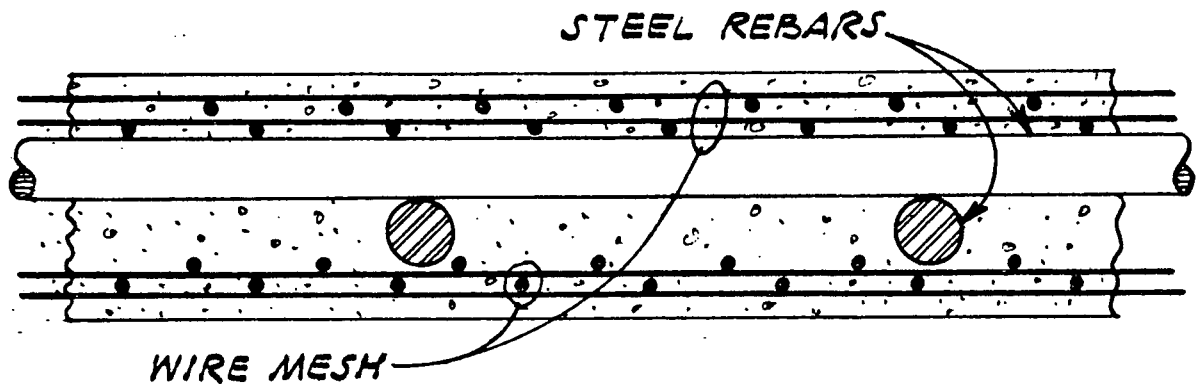
The ferro-cement concept is as old as that of reinforced concrete, but its use as a structural material has received widespread attention only in the last several decades. Ferro-cement is given a brief description and then the history of its development and current and proposed applications are summarized in the following text.

A. GENERAL PROPERTIES

Ferro-cement basically consists of a thin-shell of Portland cement mortar heavily reinforced with steel wire. The reinforcement generally consists of several layers of light gage steel wire mesh. Typical shell thicknesses are from 3/8 inch to 1-1/2 inches. Sometimes steel reinforcing bars are sandwiched between the layers of wire mesh.

Figure 1 shows two common types of ferro-cement reinforcing. Section 1a of Figure 1 shows a network of steel reinforcing bars overlain with layers of wire mesh that is impregnated with mortar. The use of reinforcing bars with wire mesh adds to the strength of the material and also provides a means of establishing the structural shape. Section 1b of Figure 1 is reinforced only with wire mesh and the required shape is obtained through external means such as casting molds. Because of the close spacing of reinforcement evident in Figure 1, care has to be taken in placement of mortar.

The material constituents of ferro-cement and those of more commonly recognized reinforced concrete are very similar, although the proportions of the materials used in ferro-cement give it several different and unique properties. The behavior of ferro-cement during strain and cracking demonstrates a synergistic effect. Because the steel reinforcing



SECTION 1a



SECTION 1b

is very evenly dispersed through the cross section, formation of cracks in the mortar is inhibited and the stress level at the onset of tensile cracking is significantly increased over plain mortar and ordinary reinforced concrete. The surface area of reinforcement is the parameter most closely related to the strain and cracking behavior of ferro-cement. Compared to ordinary reinforced concrete, ferro-cement exhibits a uniquely high surface area of reinforcement relative to its total volume. This is one of the characteristics that differentiate ferro-cement from reinforced concrete.

Much research in the last ten years has been done on a material closely related to ferro-cement, commonly referred to as "fiber reinforced concrete." This material consists of a Portland cement concrete or mortar reinforced with short, small-diameter wires. A typical wire size is 1 inch long by 0.02 inch in diameter. Chief advantages of fiber reinforced concrete are good dispersal of reinforcement and cost reductions resulting from the fact that the short fibers can be mixed and placed with the concrete or mortar matrix, using the same equipment. Because of the short fiber length, however, the principle mode of failure for this material is bond failure and wire pull-out. This type of failure is quite sudden and is undesirable in concrete structures. To date the primary applications of fiber reinforced concrete have been experimental concrete highway and airport runway slabs ranging in thickness from 4 to 6 inches. It has also been used for some thin shells. Relative to ferro-cement, however, the current state-of-the-art in fiber reinforced concrete does not warrant consideration at this time for use in the construction of wind tunnel shells. A bibliography of references on fiber reinforced concrete work, most of which were reviewed during this study, is included in Chapter IX.

B. HISTORY

The development of ferro-cement as a structural material has centered around its applications for the construction of marine craft. One of

the first uses of ferro-cement and of reinforced concrete of any type was the construction of several small boats in France by Lambot in 1855.¹ But the modern development of ferro-cement began in the early 1940's with the Italian engineer Pier Luigi Nervi. He designed and built a number of sailboat and motorboat hulls, as well as some architectural structures, using thin-shell ferro-cement construction. His investigations into the properties of ferro-cement can be summarized in the following statement:

The fundamental idea behind this new reinforced concrete material ferro-cement is the well known elementary fact that concrete can stand large strains in the neighborhood of the reinforcement and that the magnitude of stress depends on the distribution and subdivision of the reinforcement throughout the mass of concrete.²

Since the 1940's the majority of ferro-cement construction has been amateur-built, "backyard" boats ranging up to 60 feet in length. Poor results from some of these early projects caused ferro-cement to fall into some disrepute as a legitimate structural engineering material. Within the last decade, however, its potential has been recognized by a number of serious commercial boatbuilders as well as public and private research institutions around the world. Commercially built fleets of sailboats, power vessels, and cargo barges now exist or are planned in the United States, Canada, the United Kingdom, Australia, New Zealand, the Soviet Union, and China. Basic research on the engineering properties of ferro-cement has been carried out in most of these countries. A large amount of the research work done to date has been valuable in determining the engineering properties of the material; more work is now in progress, and more is needed to establish ferro-cement as a viable engineering material for general structural use. In Chapter III of this report the current state of knowledge of ferro-cement is summarized and areas requiring additional research are pointed out.

C. USES OF FERRO-CEMENT

As stated in the preceding section, the primary focus in ferro-cement development and construction has been in marine craft hulls. The material is especially suited to this type of construction because it can be molded or formed into virtually any shape in a monolithic unit. It also has relatively high rigidity, relatively high compressive and flexural strength and resistance to cracking, and is low in material cost relative to other boat-building materials. Also, it is highly resistant to fire and most corrosive elements and is easily repairable.

Marine craft that have been built of ferro-cement include private sailing and motor yachts from 30 feet to 60 feet in length, as well as commercial fishing and cargo vessels up to 180 feet long. The Naval Civil Engineering Laboratory at Port Hueneme, California, has studied ferro-cement for prefabricated construction panels.³ The Canadian government is currently sponsoring basic research and prototype construction of ferro-cement cargo barges.⁴ The United States Navy Naval Ship Research and Development Center is presently engaged in research and prototype construction of 24-foot, high-speed motor launches with ferro-cement hulls as thin as 3/8 inch.⁵ Ferro-cement has also been used extensively for the construction of marina floats.

Pier Luigi Nervi also pioneered the use of ferro-cement for buildings and other civil engineering structures. He used ferro-cement in applications such as walls for small buildings and precast units for stadium roofs. Ferro-cement has more recently been used for lining mine shafts and tunnels in Eastern Europe and for decorative paneling in Australia.⁶ Its use has been proposed for many types of tanks, including liquid natural gas containers.⁷

Architectural and civil engineering applications of ferro-cement have not kept pace with marine applications since Nervi's first use of the

material. There appear, however, to be definite cost advantages to ferro-cement in certain kinds of applications. It is a material that can be engineered to a high degree of precision, yet can be constructed by semi-skilled or unskilled labor, using relatively inexpensive materials. As more is learned about the engineering properties of ferro-cement, these advantages should lead to wider usage for many types of civil engineering structures as well as marine structures.

A major ferro-cement study is currently being sponsored by the National Academy of Science.⁸ The purpose of this study is to establish the engineering properties of ferro-cement sufficiently well that its low material costs and labor-intensive fabrication can be utilized by developing countries for applications such as marine craft and grain storage structures.

III. THE STATE-OF-THE-ART IN FERRO-CEMENT

The state-of-the-art pertaining to important ferro-cement characteristics including current information on the engineering properties of the material and the various techniques by which ferro-cement structures are being fabricated is presented in this chapter.

Most ferro-cement work to date has been related to marine construction. Applications in other fields will undoubtedly give rise to questions about its material properties and fabrication methods. Recommendations are made where the necessity for additional work on material properties or fabrication techniques is indicated, especially in relation to its use for wind tunnel construction. These recommendations are summarized in Chapter VIII of this report.

The important material properties of ferro-cement cover a wide range of engineering design parameters. The following discussions are based on review and analysis of current ferro-cement research and construction practice as well as consultation with individuals active in these fields. Building codes or standardized design procedures have not been established for ferro-cement. The following sections, therefore, present quantitative information as well as insight into the characteristics and behavior of ferro-cement so that appropriate, economical design methods can be developed for specific structural applications.

A. STRENGTH PROPERTIES

The behavior and capacity of ferro-cement subjected to various kinds of static load as well as fatigue and impact loads are discussed in the following sections.

1. Compressive Strength

Ferro-cement compressive strength is primarily dependent on the compressive strength of the mortar matrix. Typical ultimate values are 5,000 to 10,000 psi at 28 days. Based on work at the Massachusetts Institute of Technology in 1969, J. F. Collins and J. S. Claman⁹ reported that the inclusion of wire mesh reinforcement does not significantly increase or decrease the ultimate mortar compressive strength. Based on the requirements of the American Concrete Institute Building Code (ACI 318-63) Requirements for Working Stress Design of Concrete, ferro-cement working stresses should be limited to 25 percent of ultimate in uniaxial compression and 45 percent of ultimate in flexural compression.

2. Tensile Strength

The behavior of ferro-cement in tension represents a significant departure from that of ordinary reinforced concrete. As a result of the high degree of dispersion of reinforcement, the first tension cracks in the mortar matrix form at stress levels significantly higher than for unreinforced mortar or ordinary reinforced concrete. In addition, crack spacing is generally close and crack width is small. The dispersal of small diameter reinforcement in the mortar results in a material that exhibits a relatively homogeneous behavior during strain and cracking.

The two most significant points of interest in the tensile behavior of ferro-cement are the stress at formation of the first crack in the mortar and the ultimate strength. Figure 2 shows the load-elongation relationship for a typical tensile test reported in 1970 by S. P. Shah of the Department of Materials Engineering, University of Illinois at Chicago Circle.⁷ The material undergoes elastic elongation prior to first cracking, which is a distinct point in the material behavior. After first cracking, the behavior is quasi-elastic with a reduced modulus.

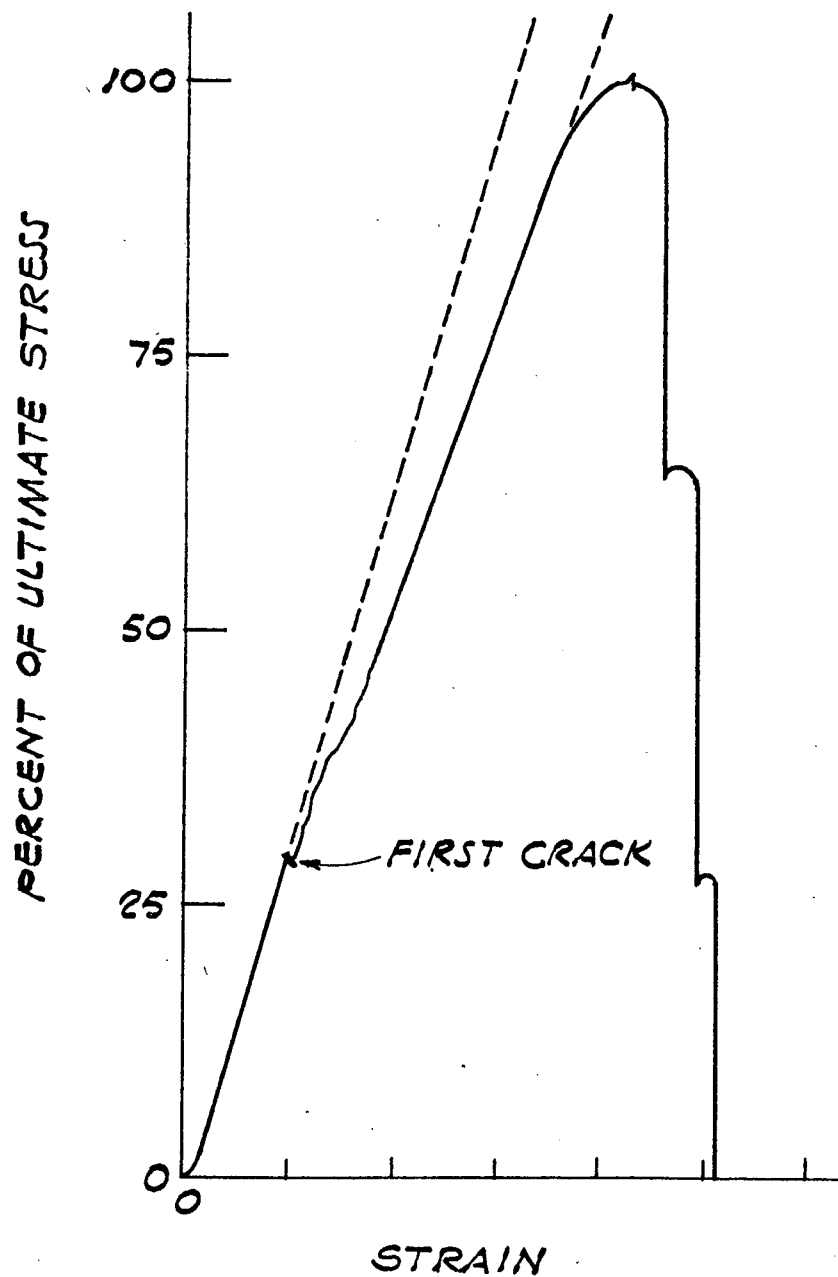


FIGURE 2 - TYPICAL TENSILE LOAD-
ELONGATION BEHAVIOR
(FROM REF. 7)

The formation of a tensile crack through the ferro-cement cross section is the result of an accumulation of micro-cracks in the material, which begin forming at low load levels and increase in numbers as the load is increased. The presence of micro-cracks is typical of cementitious materials. In ferro-cement, however, the wide dispersion of reinforcement throughout the mortar matrix restricts the propagation of these micro-cracks to the vicinity of an individual wire. The formation of the first observable crack indicated in Figure 2 is the point where the micro-crack width becomes large enough that a crack propagates through the entire section.

As tensile stress is increased following the first crack, additional cracks occur. Both formation and widening of cracks are related to localized bond failure in the vicinity of the micro-cracks, but the wide dispersion of reinforcement restricts the extent of bond failure. This results in a larger number of cracks of small individual width.

The stages of loading and cracking of ferro-cement have been reported in more detail based on recent work in Poland by J. R. Walkus and T. G. Kowalski.⁶ The behavior of ferro-cement in tension (and similarly in flexure) is summarized in Figure 3 and in the following statement from their work:

In the initial stage the material behaves in a linearly-elastic manner when loaded. Elastic deformations occur at this stage in both metal [wire mesh reinforcement] and crystalline grids [hydrated cement crystals] as well as in colloids [unhydrated materials].

With a further increase in stress, ferro-cement becomes quasi-elastic. The relatively small plastic strains of the colloids are restrained by the elastic deformation of the metal wires...The micro-cracks are invisible to the naked eye and are difficult to observe even when optical instruments are used. When the load is released, even optical instruments will not enable the positions where the micro-cracks have occurred to be detected -- such is the extent of their closing-up.

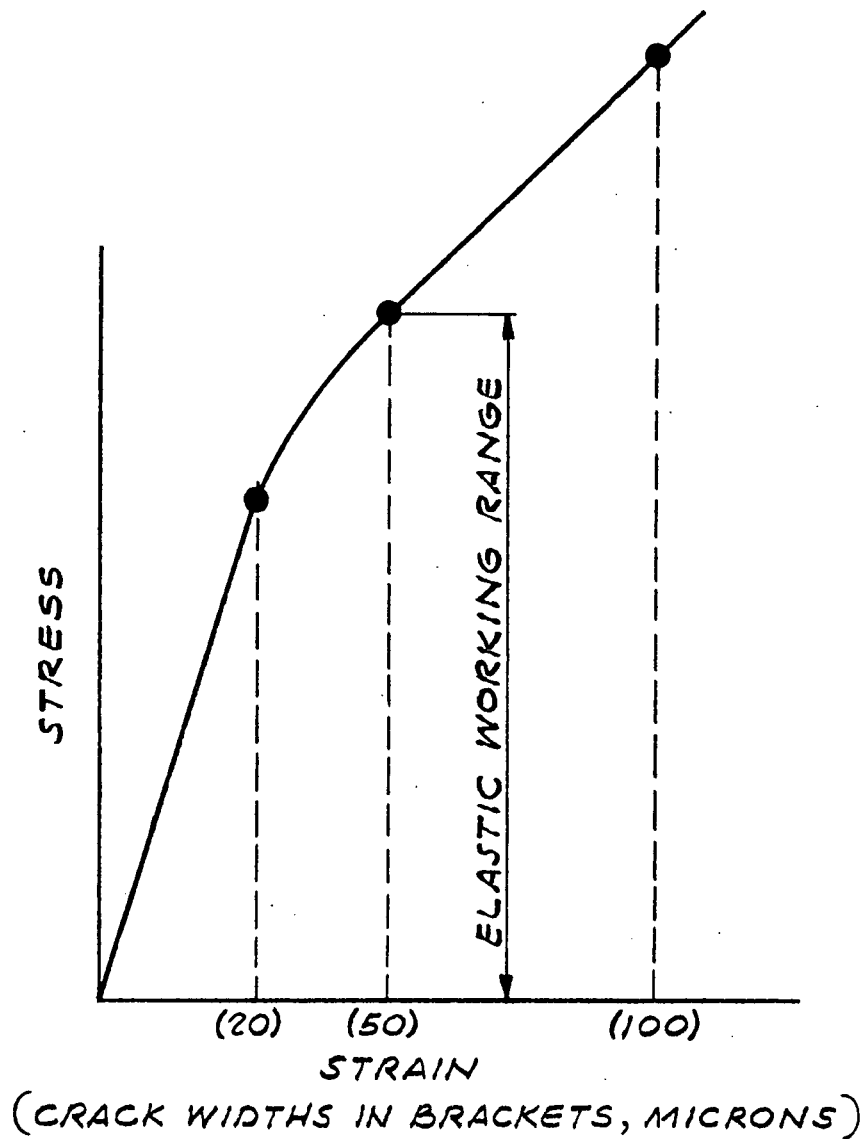


FIGURE 3a

STAGE	MATERIAL STATE	CRACK WIDTH, MICRONS	TECHNOLOGICAL STATE
I	LINEARLY-ELASTIC	20	COMPLETE WATERTIGHTNESS
II	QUASI-ELASTIC	50	NONCORROSIVE I
	ELASTO-PLASTIC	100	NONCORROSIVE II
III	PLASTIC	>100	CORROSIVE

FIGURE 3b

FIGURE 3 - WORKING STAGES OF FERRO-CEMENT
(FROM REF. 6)

These two stages -- the linearly-elastic and the quasi-elastic -- constitute the practical elastic working range of ferro-cement. A further increase in stress caused very definite plastic deformation of the colloids as well as crystalline grids, which is in turn resisted by the metallic grids of the reinforcement. This is the time of the formation and widening of exploitational cracks [i.e., cracks caused by loading]...

After the 50-micron limit has been reached the process of crack widening continues at a uniform rate. Cooperation between concrete and steel continues up to the attainment of a crack width of 100 microns and thereafter the steel alone carries all the tensile forces.⁶

The Technological State shown in Figure 3b refers to the dependence of ferro-cement corrosion resistance on crack width. This is discussed further in the section on corrosion resistance.

The first crack strength of ferro-cement in tension has been found to be related to volume percentage of reinforcement and surface area of reinforcement. The most significant of these two parameters has been found to be surface area of reinforcement.^{6,7,10,11} The most commonly used measure of this quantity is specific surface of reinforcement (S_p), which is defined as the surface area of the reinforcement (in direction of load) divided by the total volume of ferro-cement. For the same volume of wire reinforcement, a large number of small diameter wires has a high value of specific surface while a small number of large diameter wires has a lower specific surface value.

Figure 4, from experimental studies by S. P. Shah,⁷ shows an increase in the tensile cracking stress of the ferro-cement related to an increase in the steel content. Figure 5a, also from Shah's work, shows a strong relationship between stress at first crack and specific surface of reinforcement. The tests represented in Figure 5a show first cracking stress is increased by a factor of about three over unreinforced mortar for high values of specific surface. This result demonstrates a synergistic effect in ferro-cement wherein the presence

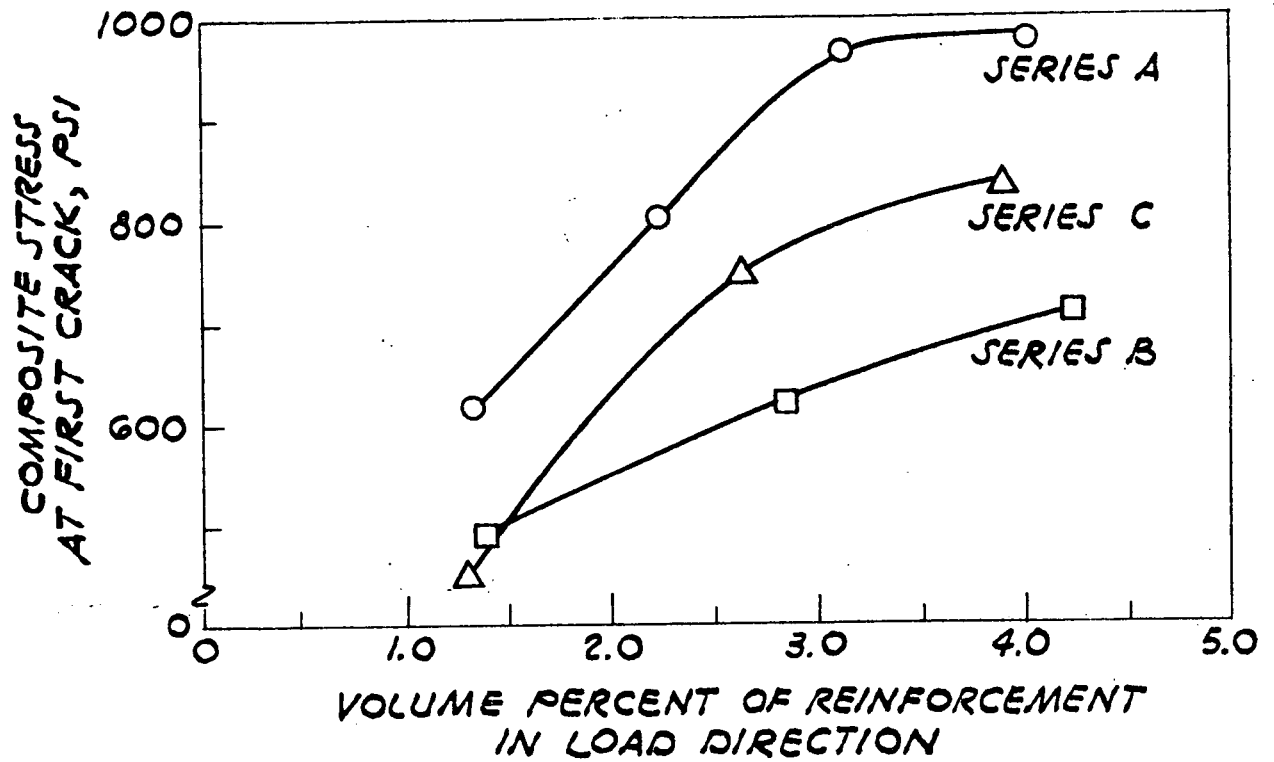


FIGURE 4 - TENSILE STRESS AT FIRST CRACK VS.
VOLUME OF REINFORCEMENT
(FROM REF. 7)

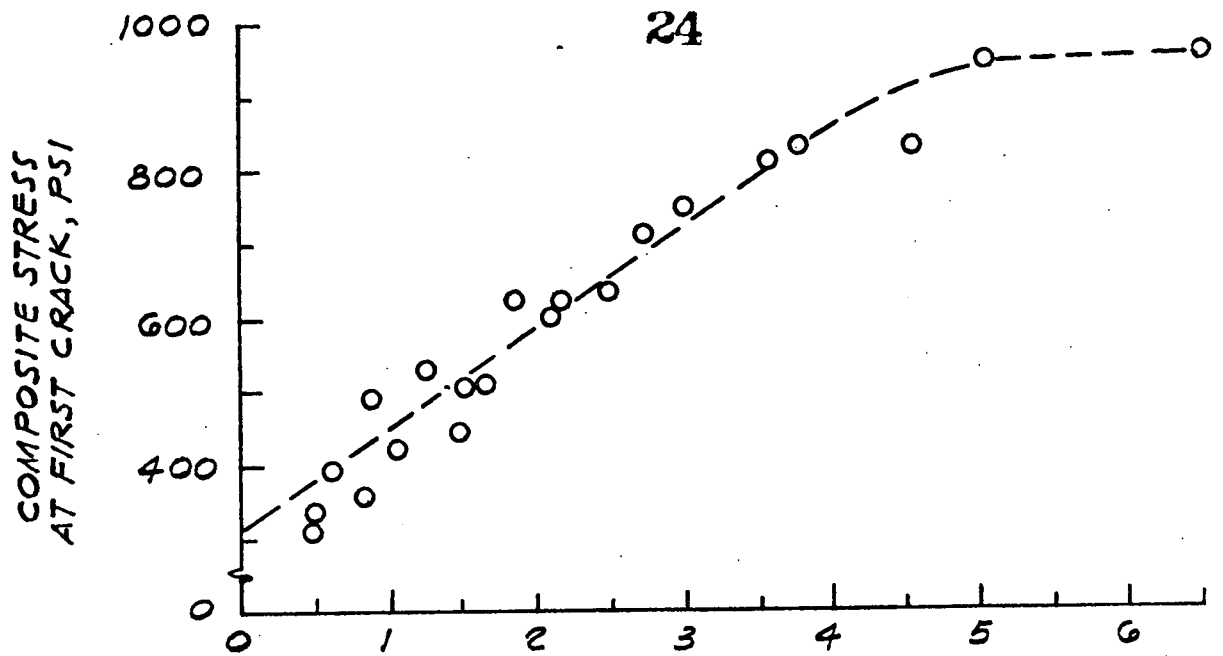


FIGURE 5a SPECIFIC SURFACE OF REINFORCEMENT
IN LOADING DIRECTION, IN^2/IN^3

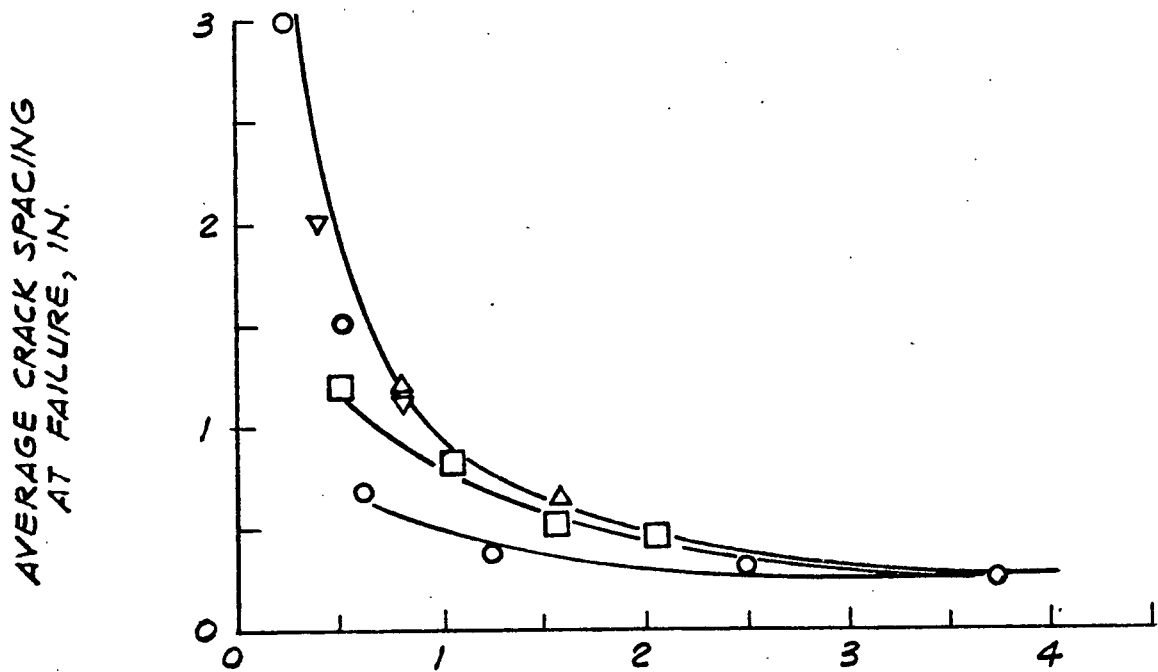


FIGURE 5b SPECIFIC SURFACE OF REINFORCEMENT
IN LOADING DIRECTION, IN^2/IN^3

FIGURE 5 - TENSILE CRACKING BEHAVIOR VS. SPECIFIC
SURFACE OF REINFORCEMENT (FROM REF. 7)

of wire mesh improves the tensile cracking behavior of the mortar matrix. Figure 5b shows a relationship between decreased crack spacing (hence decreased crack size) and increased specific surface of reinforcement.

Although the first cracking strength of ferro-cement is improved by the use of wire reinforcement, the first cracking strength is usually well below the ultimate capacity. For many structural applications of ferro-cement, the presence of cracks of a limited size may not be detrimental. Shah has proposed a ferro-cement design procedure based on a maximum specified allowable crack width under service loads.¹² For example, allowable crack widths would be quite low for structures that must be watertight or resistant to corrosive elements, and relatively higher for structures in a less harsh environment. Shah is currently conducting studies to establish a relationship between crack width, specific surface of reinforcement, and reinforcing steel stress for ferro-cement in tension. A hypothetical set of design curves based on this kind of research is shown in Figure 6. Specification of the maximum allowable crack width and selection of a value of a specific surface would give an allowable design stress.

No direct relationship has been found between the tensile cracking behavior of ferro-cement and the properties of the mortar matrix. During ferro-cement testing at MIT in 1969, however, J. F. Collins¹³ observed that poor bonding between mortar and steel mesh leads to a lower tensile cracking strength. Poor bond in the wires perpendicular to the direction of stress creates the equivalent of a void in the region of the wire. This leads to stress concentrations and premature cracks perpendicular to the direction of stress. Based on this finding, care should be taken in mix design and preparation of reinforcement to insure proper bond.

The ultimate tensile strength of ferro-cement has been found by Shah⁷ to be dependent solely on the tensile capacity of the reinforcement. This is clearly demonstrated by the test results shown in Figure 7.

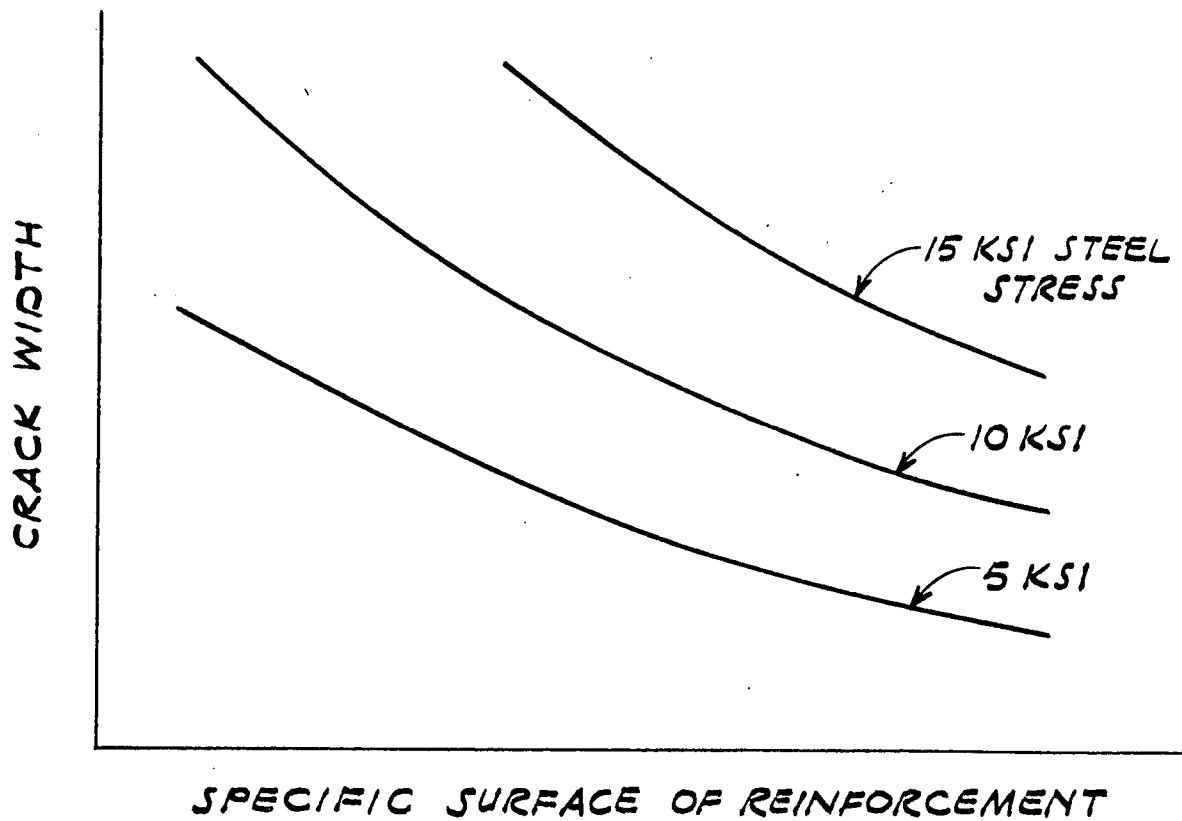


FIGURE 6 - HYPOTHETICAL FERRO-CEMENT DESIGN CURVES BASED ON CRACK WIDTH

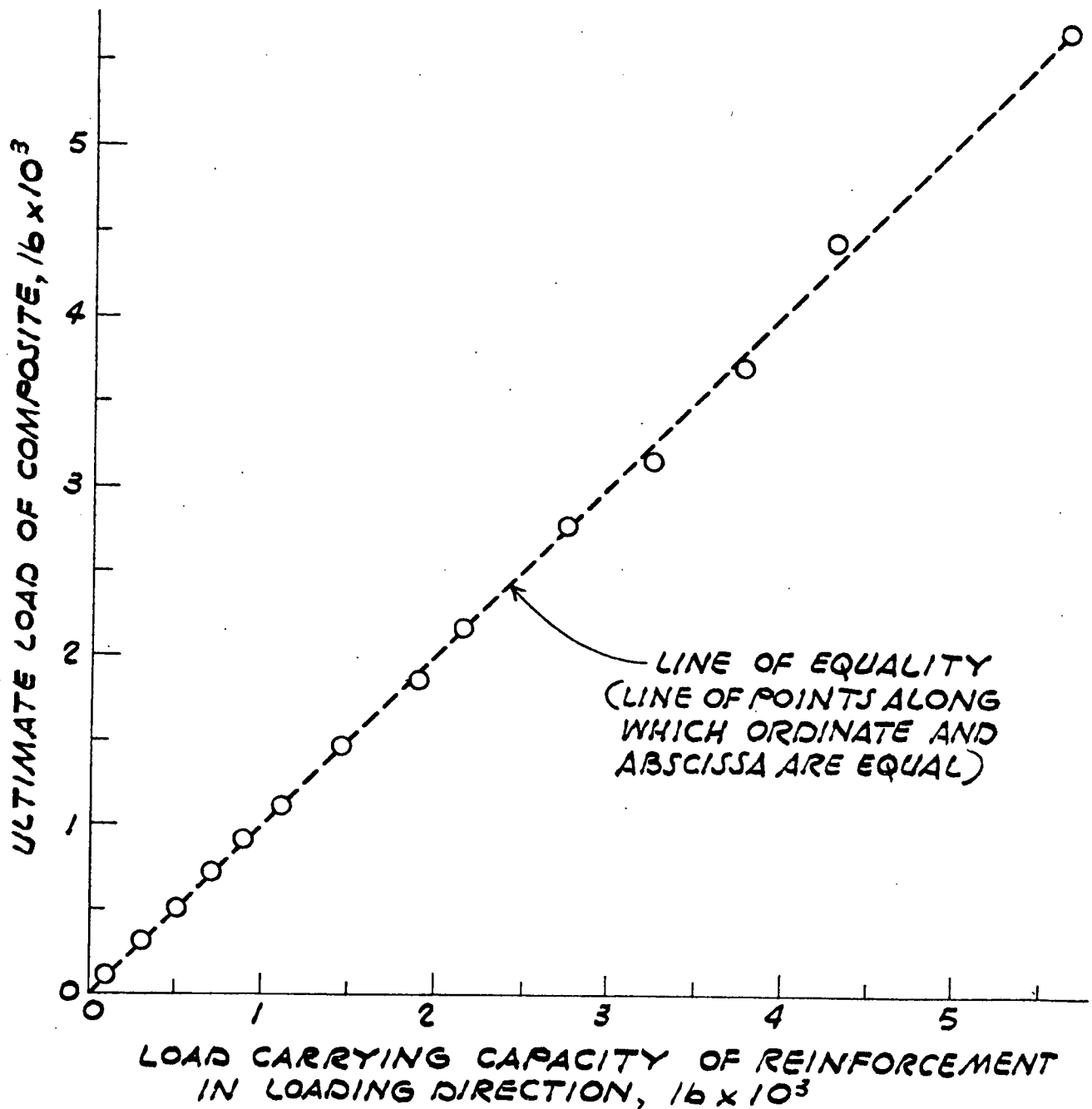


FIGURE 7 - ULTIMATE LOAD OF COMPOSITE VS.
ULTIMATE CAPACITY OF REINFORCEMENT
(FROM REF. 7)

3. Flexural Strength

Ferro-cement in bending exhibits unique properties much like those discussed for tension. A relationship between increasing stress at first crack and increased volume and specific surface of reinforcement has been observed, and at ultimate flexural capacity its strength is related primarily to the capacity of the reinforcement.

Typical load-deflection curves from flexural tests conducted in 1970 by J. E. Tancreto and H. H. Haynes of the Naval Civil Engineering Laboratory, Port Hueneme, California,¹⁴ are shown in Figure 8. Similar to tension, flexure behavior exhibits an initial linear deflection followed by cracking of the mortar and further linear deflection prior to yield and ultimate failure. The observations of Walkus and Kowalski⁶ which are summarized in Figure 3, also apply to the flexural behavior of ferro-cement. Based on their findings the elastic behavior is limited by the formation of the first loading crack. The first visible crack observed by Tancreto and Haynes (Figure 8), however, is probably at a higher stress level than the elastic limit proposed by Walkus and Kowalski.

Figure 9, which contains data obtained by Tancreto and Haynes, shows a relationship between increased specific surface of reinforcement and increased flexural stress at first crack. The formation of flexural tension cracks results from the same behavior as discussed for pure tension cracks. These cracks reduce the flexural rigidity of the cross section. Its effect is observed as a reduction in the modulus of elasticity for a flexural load test. This behavior is verified in work done at MIT¹⁵ and the University of Michigan.¹⁶

The concept of a design procedure based on crack width as related to stress and specific surface being studied by S. P. Shah¹² can also be applied to ferro-cement in flexure. A design criterion

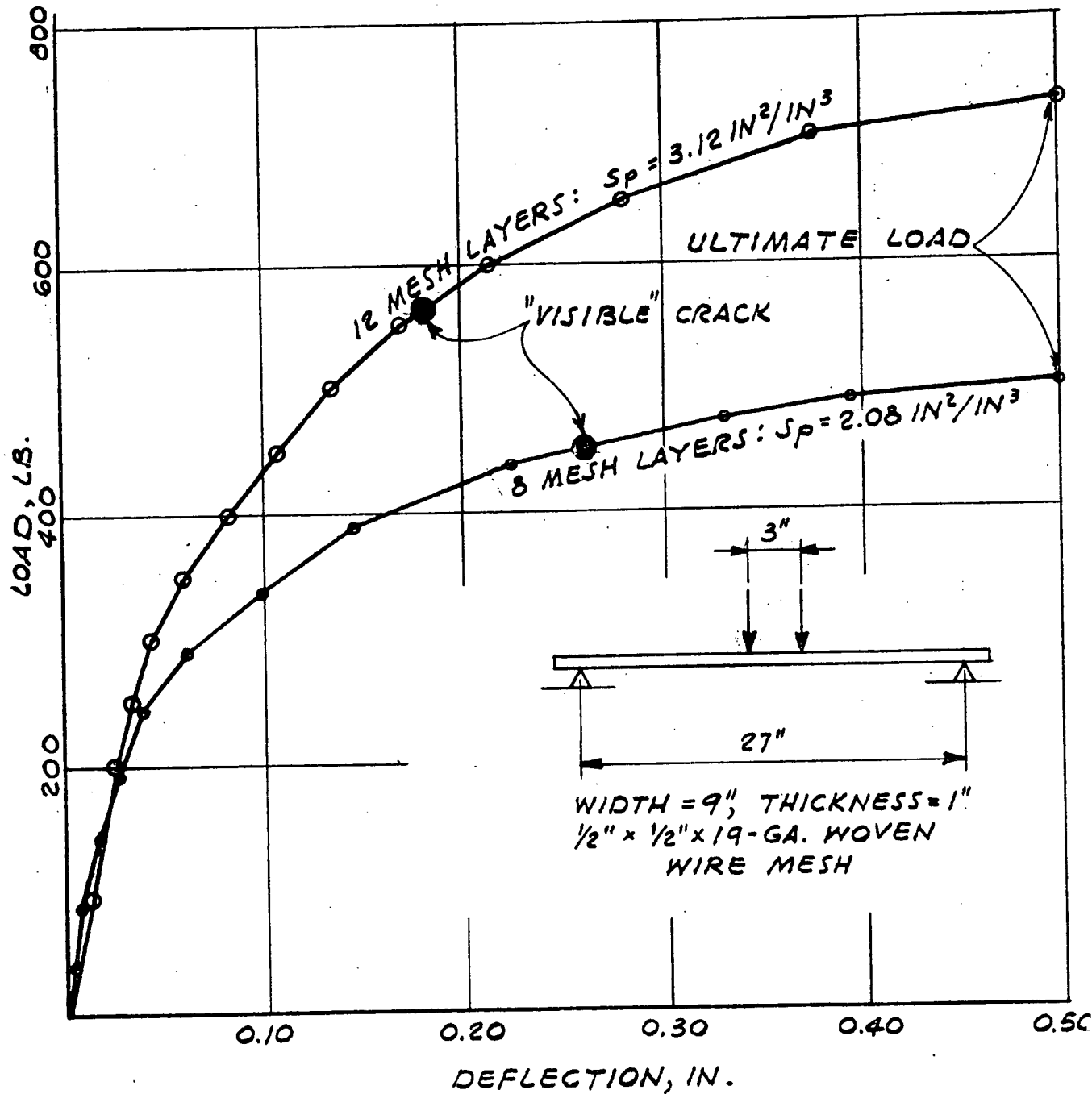


FIGURE 8 - TYPICAL FLEXURAL LOAD-DEFLECTION BEHAVIOR (FROM REF. 14)

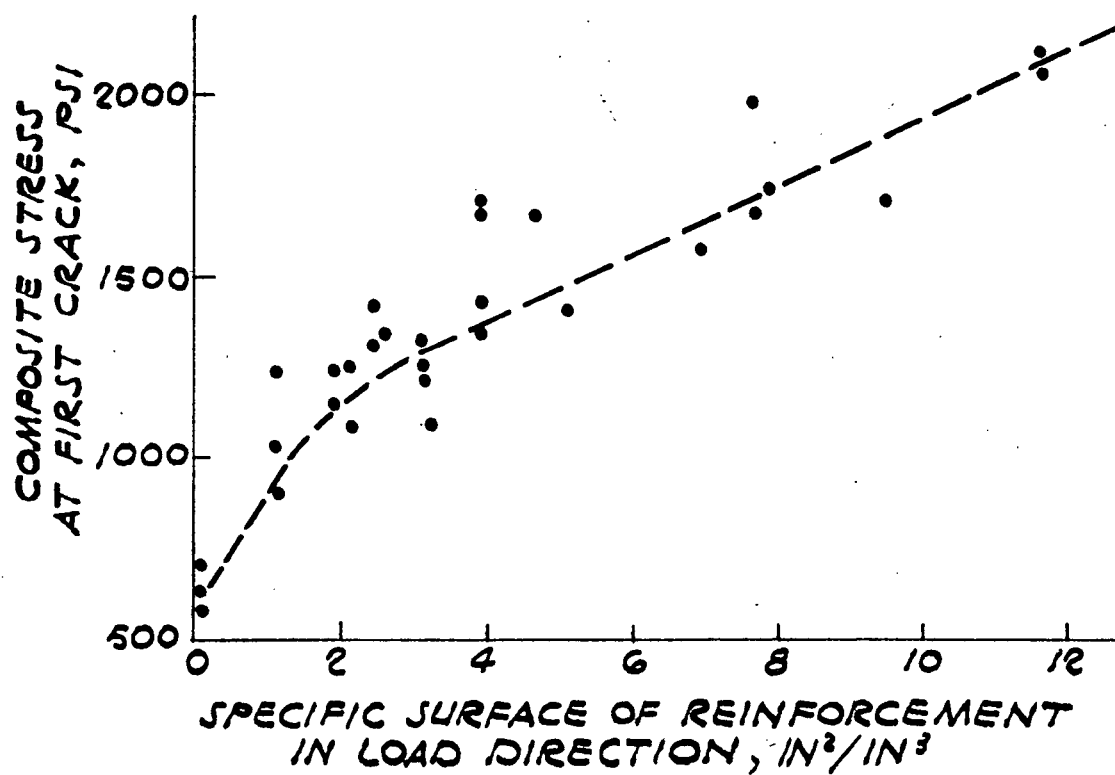


FIGURE 9 - FLEXURAL STRESS AT FIRST CRACK VS.
SPECIFIC SURFACE OF REINFORCEMENT
(FROM REF. 14)

based on maximum allowable crack width under service loads for a given structural application would then permit selection of an optimum reinforcement configuration and corresponding allowable design stress. The current work by Shah is being done for pure tensile stress only. Additional work would be required to establish design curves of this type for ferro-cement in flexure.

An experimental method for studying concrete is currently being used at the University of California at Berkeley whereby very thin sections are cut from specimens after loading and studied microscopically.⁸ Such a method could be used to observe the formation and width of cracks and also the elastic and inelastic deformation behavior of mortar and reinforcement.

Unlike its behavior at cracking load, the behavior of ferro-cement at ultimate flexural capacity demonstrates a primary dependence only on the ultimate load carrying capacity of the steel reinforcement. This result corresponds to similar findings mentioned above for the tensile strength of ferro-cement. Tancreto and Haynes¹⁴ have found that the ultimate flexural capacity of ferro-cement can be predicted quite accurately by computing the capacity of a cross section consisting only of the reinforcing steel using the following equation:

$$M_{ult} = f_{ult} \left(\frac{I}{c} \right)$$

where

M_{ult} = Ultimate flexural moment, in.-lb.

f_{ult} = Ultimate tensile strength of wire reinforcement, psi

I = Moment of inertia of wires about neutral axis, in.⁴

c = Distance from neutral axis to extreme tension wire, in.

The use of steel reinforcing bars in addition to wire mesh (Figure 1), which increases the volume percentage of reinforcement, gives higher reinforcement capacity and hence higher ferro-cement ultimate moment.

4. Shear Strength

There is a limited amount of shear strength data available with respect to design of ferro-cement for shear loads. Available data indicate that shear strength is dependent on the volume of reinforcement for shear loading normal to the plane of the material.

Results of some of the earliest ferro-cement research work, done in 1959 in Ireland by L. D. G. Collen and R. W. Kirwin,¹⁷ given in Figure 10, show increased shear strength is related to increased steel content. These results are substantiated by Claman's¹⁵ observation that the inclusion of reinforcing bars in the cross section, which generally increases steel content, results in increased shear capacity.

In his work at MIT, Claman¹⁵ observed that the yielding of ferro-cement in shear under loading normal to the plane of the material is accompanied by slippage of the reinforcement and abrupt change in the slope of the load-deflection curve. This kind of behavior is undesirable and should be considered to represent the ultimate shear load of ferro-cement. To prevent this kind of yielding, design shear stress should be kept well below this level, similar to the design of reinforced concrete members without shear reinforcement. Although design shear stress will be relatively low, flexural or tensile stresses are generally more critical for thin-shell structures.

5. Modulus of Elasticity

Studies of the modulus of elasticity of ferro-cement show a relationship between increased volume percentage of reinforcement in the

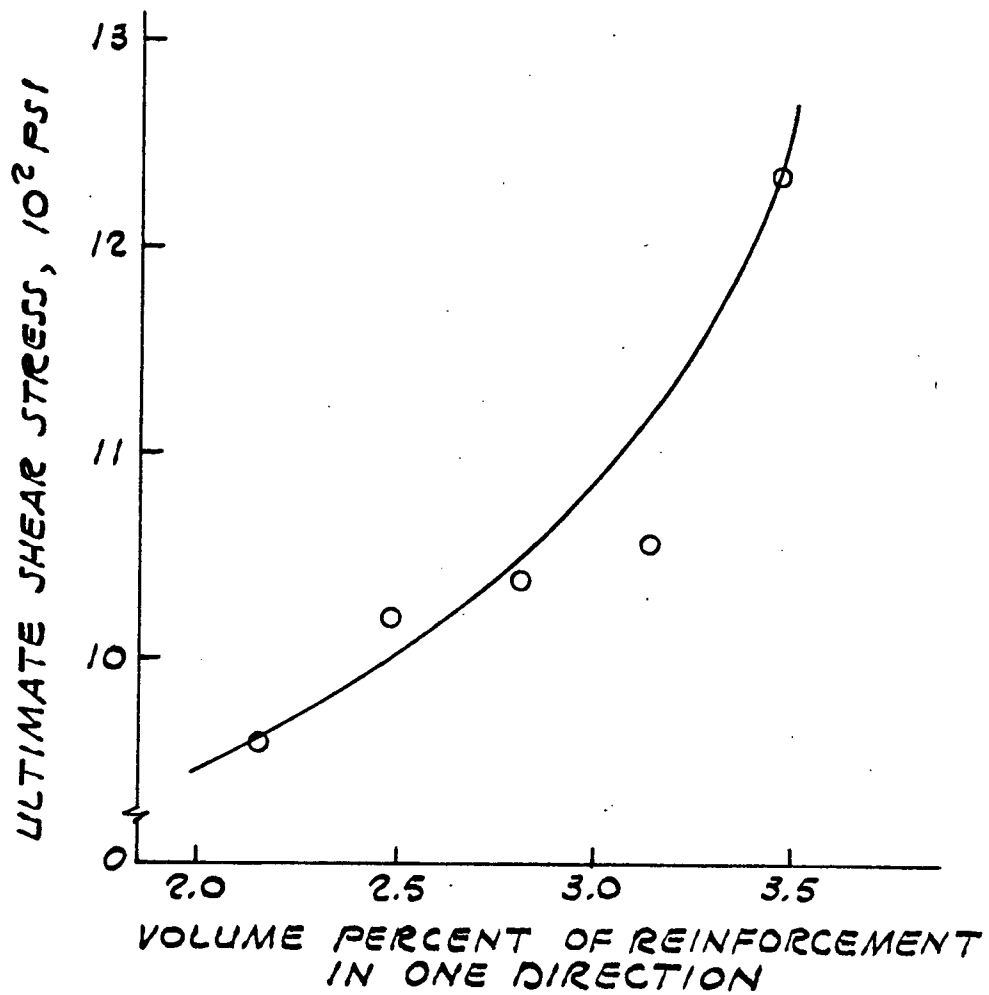


FIGURE 10 - ULTIMATE SHEAR STRESS
VS. VOLUME OF REINFORCEMENT
(FROM REF. 17)

direction of loading and increased modulus. A distinct decrease in modulus after formation of first crack has been observed in most studies.

The load-elongation curve for a ferro-cement tensile test shown in Figure 2 shows a decrease in modulus of elasticity after the first crack. Similar two-phase behavior for flexure tests has been found by Tancreto and Haynes (Figure 8) but the change in slope is generally less abrupt. Shah has found that an estimate of the modulus of elasticity in tension can be obtained from the law of mixture of composite materials as follows:⁷

$$\text{Before first crack: } E = E_M + E_{RL} V_L$$

$$\text{After first crack: } E = E_{RL} V_L$$

where

E = Modulus of elasticity of ferro-cement

E_M = Modulus of elasticity of mortar

E_{RL} = Modulus of elasticity of mesh in load direction

V_L = Volume fraction of reinforcement in load direction

The test results by Shah for modulus of elasticity of ferro-cement in tension are shown in Figure 11. It can be seen that modulus of elasticity is directly related to volume of reinforcement. This was also observed in early research in Ireland by Collen.¹⁷

The modulus of elasticity of ferro-cement in flexure or compression has not been studied in detail; however, a dependence on mortar strength and

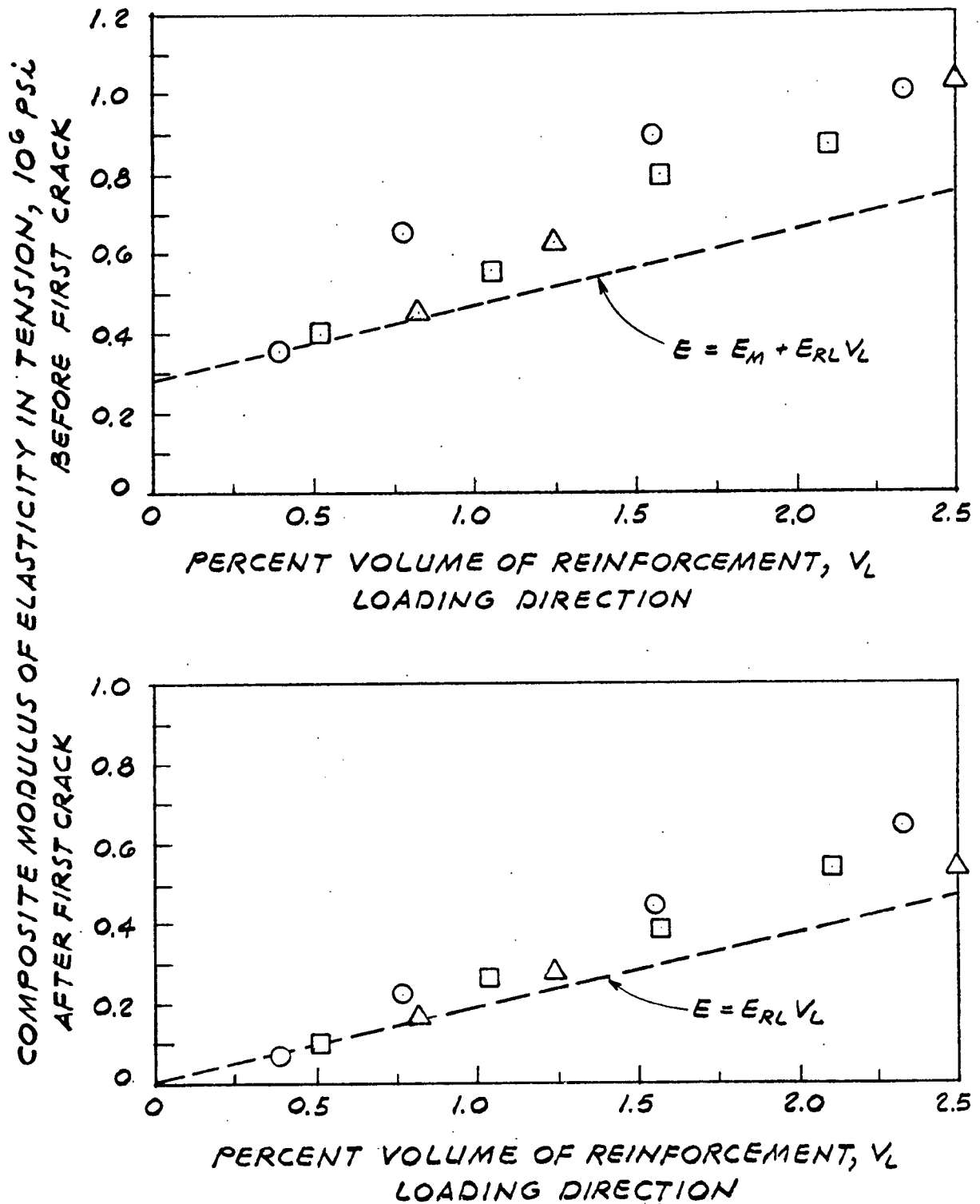


FIGURE 11- COMPOSITE MODULUS OF ELASTICITY IN TENSION
(FROM REF. 7)

volume of reinforcement, similar to tension would be expected. The load-deflection results of Tancreto and Haynes¹⁴ indicate values for flexure of about 4,000,000 psi before cracking and about 1,000,000 psi after cracking.

6. Fatigue Resistance

Ferro-cement behavior under repeated loading has been largely ignored in published research work, although recent unpublished testing work in the Naval Ships Research and Development Center at Annapolis included some fatigue study. It is expected that fatigue resistance of ferro-cement will be dependent on volume and specific surface of reinforcement, similar to the behavior of ferro-cement under tensile and flexural static loading, and also on the range and magnitude of cyclic loading.

Some early fatigue test results were obtained in about 1963 by an English builder of ferro-cement boats, Windboats, Ltd.¹⁸ Results are for bending fatigue of four samples 22 inches by 5 inches by 0.65-inch thick, and are as follows:

Sample	Nominal Stress Levels, psi	Cycles	Remarks
A	+625 -544	2,000,000	cracked
B	+700 -600	2,000,000	no fracture
C	±1100	100,000	cracked
D	±1185	100,000	cracked

More recent work completed in 1971 by the United States Naval Ships Research and Development Center¹⁹ is shown in Figure 12. These data show test results for samples with 6.5 percent reinforcement,

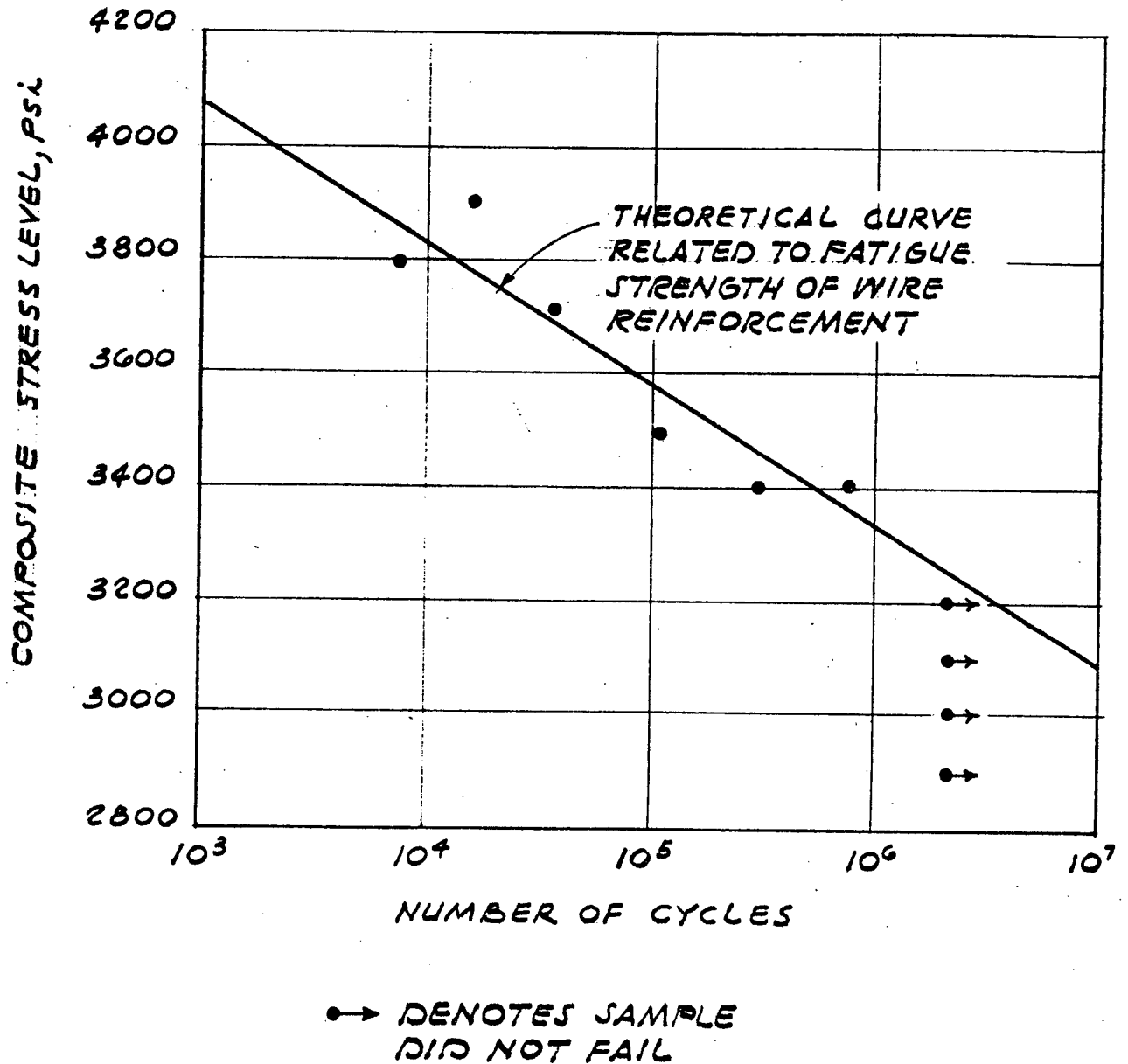


FIGURE 12 - FERRO-CEMENT FATIGUE TESTS
(FROM REF. 19)

measuring from 3-to 6-inches wide and constant thickness, loaded as cantilever beams with a 6-inch constant strain zone. Loading range was from positive maximum load to negative maximum load and the frequency was from 6-to 18-cycles per minute. The datum points represent the point when "fatigue cracks were noted or when the specimen had accumulated 2,000,000 cycles." The theoretical curve indicated is based on fatigue data for the wire reinforcement and application of the theory of transformed sections. Thus it is assumed this curve is based on fatigue failure as determined by fatigue yielding of the reinforcement. It is important to note that the loading ranges used were well above the load to cause first cracking of the mortar. The report concerning this work concluded that "based on verification of the theoretical curve by the data it appears that the endurance limit (fatigue yielding) for this ferro-cement composition is about 3,000 psi." As seen in Figure 12 this endurance limit is for a maximum of 2-million loading cycles. Static flexural tests reported in this same document indicate that the static stress to produce reinforcement yielding is about 6,200 psi. Thus the fatigue limit of 3,000 psi appears to represent about 50 percent of the static yield stress.

The above test results provide important and useful fatigue information. For design of important or unusual structures, however, much additional information is needed. For example, data on higher frequency loading, various loading ranges, and higher number of load cycles would be significant. A study of the long term effect of strength gain in cementitious materials on fatigue behavior of ferro-cement would also be significant. Whereas the Naval Ships Research and Development Center data (Figure 12) give useful information in the range of ferro-cement yield load, additional work is necessary to determine the effect of fatigue on the first crack load. This information would be important for structures where cracking is to be avoided. In addition, the previously described work by Shah in establishing crack width as a design parameter could be adapted to fatigue loading. Design curves would relate crack width to stress level, specific surface, and also number of fatigue loading cycles.

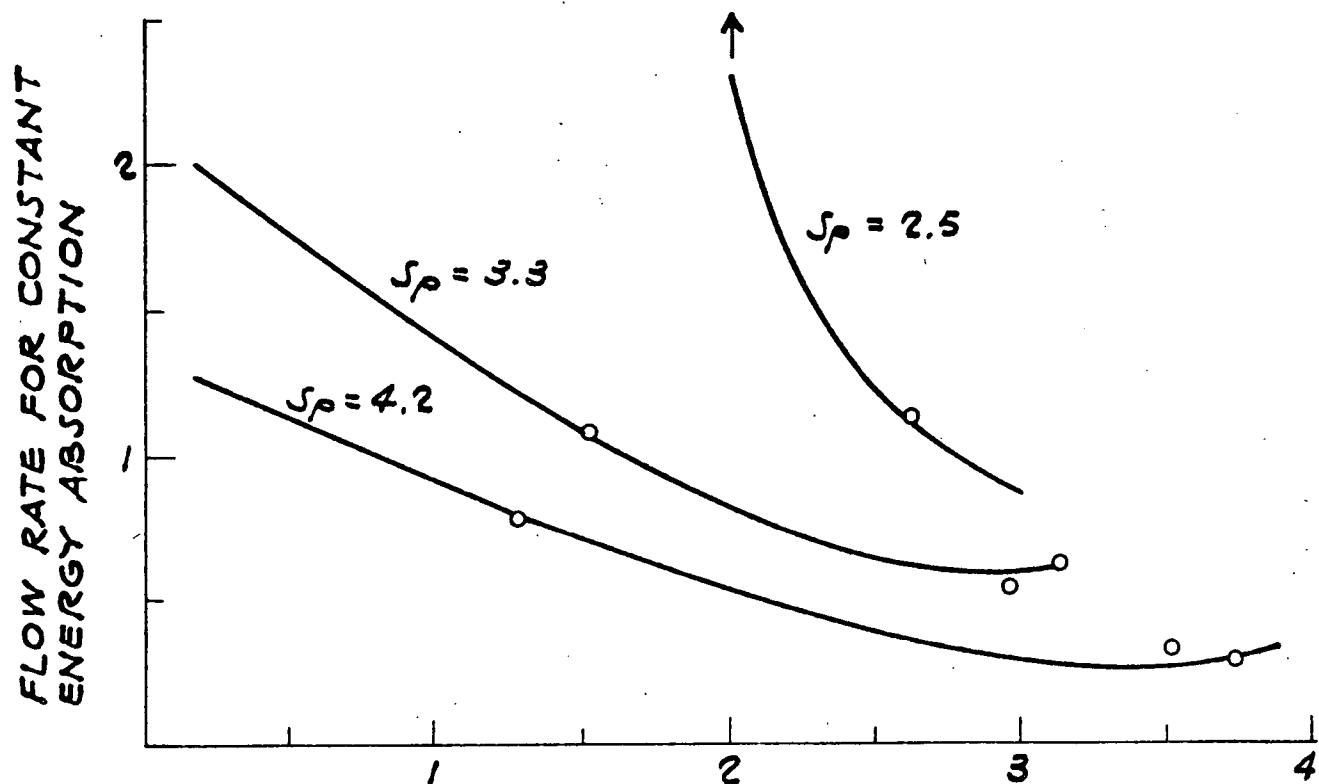
In the testing program described in this report, supervised by John A. Blume & Associates, Engineers, fatigue tests related to first crack load were carried out. These tests and results are discussed in Chapter IV.

7. Impact Resistance

The behavior of ferro-cement under impact loading is typified by high ductility and energy absorption in the plastic range, good localization of damage, and generally easy repair of damaged areas. Experimental testing has been done to compare impact resistance of ferro-cement with that of reinforced concrete, fiber reinforced plastic, and marine plywood. Material parameters affecting impact resistance have been found to be thickness of cross section, volume and surface area of reinforcement, and strength of reinforcement.

Impact studies in the Soviet Union reported in 1968 by V. F. Bezukladov¹¹ compared ferro-cement to reinforced concrete. Tests involved dropping a 10-inch sphere weighing 55 pounds on 20-by 36-inch panels of 1-inch thick ferro-cement and 2-inch thick reinforced concrete. Results indicated that the ferro-cement performed slightly better.

Tests conducted in 1970 at MIT by S. P. Shah and W. H. Key, Jr.²⁰ evaluated the effect of specific surface of reinforcement and strength and ductility of reinforcement on impact resistance. Tests involved striking 9-inch by 9-inch by 1/2-inch thick panels with a ballistic pendulum and measuring absorbed energy and damage to the panel. Damage was evaluated by measuring the leakage flow rate of water under a constant head through the impacted region. Steel reinforcement percentage was held constant while ductility and specific surface were varied. Typical results are shown in Figure 13. Both high specific surface of reinforcement and high tensile strength, low ductility steel resulted in lower leakage rate and thus, by definition lower impact damage for a constant value of absorbed impact energy.



TENSILE YIELD LOAD OF REINFORCEMENT, $lb \times 10^3$
(VOLUME OF REINFORCEMENT IS CONSTANT)

**FIGURE 13 - EFFECT OF SPECIFIC SURFACE
AND TENSILE STRENGTH OF REINFORCEMENT
ON IMPACT DAMAGE (FROM REF. 20)**

Comparison with other materials and a method for improving impact resistance were studied in 1971 by K. A. Christensen and R. B. Williamson at the University of California, Berkeley.²¹ Panels of ferro-cement, marine plywood, and fiber reinforced plastic (FRP) ranging in thickness from 1/2- to 1-1/2-inches were tested under impacts from a 25-pound hemispherical weight dropped from heights up to 18 feet. Damage was measured by the leakage flow rate of water through the damaged area. The primary focus of the tests was on establishing a single-blow "critical impact" for each type of panel that resulted in a leakage rate of 6 gallons per hour under a 2-foot head, which was defined as a "critical condition" of impact damage. Test results comparing ferro-cement to marine plywood of equal thicknesses showed that ferro-cement impact resistance varies from 50 percent less than the plywood for thin (1/2-inch) sections to approximately equal to the plywood for thicker (1-1/2-inch) sections. Results showed the FRP to be far superior, the 1/2-inch FRP section having 100 percent more impact resistance than the 1-1/2-inch ferro-cement section.

The test results by Christensen and Williamson showed that ferro-cement, similar to fiber reinforced plastic, exhibits good plastic absorption of impact energy after partial failure. A typical impact specimen was described as follows:

The top surface of the impacted ferro-cement specimens gave little evidence that the panel was in a critical condition. A smooth crater in the mortar without exposure of the mesh did not indicate that passage of water might result. Damage to the impacted surface was confined to crushing directly under the impact device. On the side opposite the impacted surface crack propagation was arrested within a small area, approximately three times the diameter of the impacting device. This was accompanied by approximately 1/2 inch bulging with virtually no loss, spalling, or breaking away of the mortar, even though there was cracking and loosening of the mortar in the mesh. The mesh restrained and retained the broken mortar.²¹

A sandwich panel designed to improve impact resistance was developed as part of their ferro-cement impact studies. This new section consists of ferro-cement overlaid with fiber reinforced plastic. A 3/4-inch sandwich panel consists typically of 1/2-inch of ferro-cement overlain with 1/4-inch of FRP. Test results showed impact resistance increased eight to ten times compared to equal thicknesses of normal ferro-cement. The materials and fabrication of these sandwich panels would be more costly than plain ferro-cement, yet this material provides a good alternative in critical impact areas of ferro-cement structures.

Christensen and Williamson note that no theoretical consideration of ferro-cement impact resistance exists and none was attempted in their report. Their work was intended to provide a guide to ferro-cement impact strength by comparison with the more widely known and documented materials, marine plywood and fiber reinforced plastic. Relative to steel, the impact strength of ferro-cement in resisting complete failure (i.e., punch-through) has been estimated by R. B. Williamson as that of a steel plate containing the same volume of steel as the total volume of the ferro-cement reinforcement.⁸ Although ferro-cement impact strength is low relative to steel and fiber reinforced plastic, good ductility of ferro-cement in absorbing impact energy after partial damage, as well as ease of repair of damaged areas, appear to make ferro-cement feasible for use in many structures where impact loads are expected.

Because of the limited impact strength of ferro-cement, tests should be developed to approximate actual anticipated impact loads, such as vehicle collision or propeller blade impact. Various ferro-cement sections should be compared and the need for strengthening such as FRP overlay or steel plate backing evaluated.

B. MATERIAL CONSTITUENTS

The basic ferro-cement materials -- mortar and reinforcement -- are discussed in the following sections. The types and proportions of these materials and their effect on various ferro-cement properties are described.

1. Mortar

The nature of ferro-cement mortar and the influence of various mix design parameters on ferro-cement mortar are important considerations. As in reinforced concrete construction, mix design in ferro-cement affects a number of material characteristics including compressive strength, drying shrinkage, density, and durability. The Portland cement mortars used in most reported ferro-cement construction projects and laboratory tests can be generally characterized as cement-rich with relatively low water content and high strength.

The types of cement used in various ferro-cement projects vary widely depending on the need for such qualities as low shrinkage, high early strength, or high resistance to corrosion. The use of sulfate-resistant cement is desirable for increased corrosion resistance as is low alkali cement for reducing the detrimental effects of alkali-aggregate reaction. Aggregates are generally fine sand, although some recent research and construction projects have used manufactured lightweight aggregates to give better uniformity of aggregate and reduced structural weight.^{22,4}

The proportion of cement in ferro-cement mortars is generally high, providing good workability and high density. Typical values for sand-to-cement ratio are from 1.0 to 2.0, although high cement content can lead to problems in drying shrinkage. Values of water-to-cement ratio from 0.33 to 0.60 have been used, although a low value is desirable

for high strength and low permeability. Zero-slump mortar has been used in conjunction with molds and vibration during placement.

Additives in ferro-cement mortar have been used primarily to improve such properties as workability and resistance to chemical attack, and to reduce drying shrinkage. The use of such additives is well-documented in concrete literature. The most commonly used have been pozzolan or fly ash to improve workability.

A significant contribution to ferro-cement technology has been the use of a chromium trioxide additive by K. A. Christensen and R. B. Williamson, Department of Civil Engineering, University of California, Berkeley.²³ Where bare steel reinforcing bars and galvanized wire mesh are used together, a galvanic cell action is set up between the steel and zinc mesh coating with the wet mortar acting as the electrolyte, causing hydrogen gas bubbles to be released. These bubbles seriously disrupt the surface quality and the bond between the mortar and reinforcing bars. The addition of chromium trioxide to the mortar mix largely inhibits this electrochemical reaction.

A number of ferro-cement characteristics including strength, drying shrinkage, durability, and economy are greatly affected by mix design. Until such time as comprehensive design procedures are developed, detailed study of mortar mix design is recommended for major structural applications. Because of the typically thin cross section and reinforcement coverage typical of ferro-cement, durability is especially dependent on good mix design. The subject of corrosion resistance is discussed further in a later section.

2. Reinforcement

The preceding sections covering the state-of-the-art in ferro-cement strength properties included considerations of reinforcement. For

clarity the various parameters related to ferro-cement reinforcement are summarized and discussed in this section.

Two commonly used reinforcement configurations are shown in Figure 1. Section 1a of Figure 1 shows the use of reinforcing bars in conjunction with wire mesh. The bars are at the center of the ferro-cement cross section and the wire mesh is laid over each side of the network of bars. Reinforcing bars are typically 1/4-inch bars on 2-inch centers while wire mesh sizes have varied greatly in recent test programs and construction projects. Typical mesh sizes have 1/2-inch or 1/4-inch wire spacing and utilize 16-to 24-gage wire.

Section 1b of Figure 1 shows a ferro-cement section using only wire mesh reinforcement. Typical mesh sizes are similar to those mentioned above. Reinforcement coverage for both sections is typically 1/16-to 1/8-inch. To maximize reinforcement volume and specific surface, the maximum number of mesh layers generally are used consistent with maintaining the required coverage within a given thickness.

Reinforcement parameters related to the strength properties and other performance characteristics of ferro-cement sections include the following:

- Volume and specific surface of reinforcement
- Size of reinforcement (diameter, spacing)
- Strength and ductility of reinforcement
- Type of reinforcement (reinforcing bars, welded wire mesh, woven wire mesh, expanded metal, "chicken wire," galvanized, ungalvanized)

The most significant reinforcement parameters are volume and specific surface. Increased volume percentage of reinforcement is related closely to increased tensile stress at first crack (Figure 4) and

increased tensile stress at ultimate load (Figure 7). The results of bending tests have related increased volume of steel to increased ultimate flexural capacity.¹⁴ Volume percentage of reinforcement directly affects the elastic modulus of ferro-cement, increased volume resulting in increased modulus (Figure 11). It appears obvious that other ferro-cement properties such as fatigue resistance are related to volume of reinforcement, although this has not been experimentally verified as yet.

The specific surface of reinforcement is the most sensitive material parameter in relation to strain and cracking behavior. It should be noted that a high value of specific surface is the principal characteristic that separates ferro-cement from reinforced concrete. The use of reinforcing bars in ferro-cement improves some material strength properties through increases in reinforcement volume, but the only way of obtaining significantly high specific surface is through the use of wire mesh reinforcement, or similar materials such as expanded metal lath, which provide good reinforcement dispersal.

Increased ferro-cement stress at first cracking for both flexure and tension is very closely related to increased specific surface (Figures 5 and 9). Impact resistance is similarly related to specific surface (Figure 13). Several ferro-cement research reports have stated that a high value of specific surface is one of the primary factors that distinguish it from reinforced concrete. I. R. Walkus and T. G. Kowalski⁶ state that a specific surface of reinforcement greater than about 2.5-inch²/inch³ delineates ferro-cement from ordinary reinforced concrete.

The size and spacing of reinforcement are the primary variables in establishing the value of the specific surface. In general, smaller diameter wires spaced closer together result in higher specific surface of reinforcement. The ease of construction is also affected by size and spacing of reinforcement. The use of more widely spaced wire mesh allows easier and better mortar penetration.

Because the ultimate strength of ferro-cement in tension and flexure is directly related to reinforcement capacity, the strength of reinforcement is similarly related to these material properties. A higher strength (less ductile) steel results in higher load and smaller cracks at ultimate load. Higher impact resistance (Figure 13) is also related to higher strength steel.

Several kinds of reinforcement have been successfully used in ferro-cement construction. The use of steel reinforcing bars along with wire mesh gives increased flexural stiffness and increased flexural yield. The inclusion of reinforcing bars also has been observed to improve shear strength. The most commonly used wire reinforcements are woven wire mesh and welded wire mesh. Expanded metal lath and chicken wire have also been used. Comparative studies of various reinforcements have shown certain weaknesses in some types. Woven wire mesh and expanded metal lath reinforcement result in variation in the ferro-cement tensile properties in the two orthogonal directions. For woven wire mesh with large weave angle and also for chicken wire reinforcement, spalling of the mortar matrix has been observed at the ultimate load of the reinforcement. It should be noted, however, that the above materials have been used successfully in marine applications where service loads are well below ultimate value. The use of expanded metal lath can, in fact, result in very high values of specific surface.

Ungalvanized wire mesh has been found to provide greater ultimate strength because the process of galvanizing anneals and weakens wire. Also, ungalvanized woven wire mesh has been found to be desirable when tight curvatures or double curvatures are encountered because there is no bonding between orthogonal wires and it is therefore easier to form. However, except when protective surface coatings are used, galvanized reinforcement is generally desirable for increased corrosion protection because of the relatively thin mortar coverage over the reinforcement in most ferro-cement sections.

Optimization of the reinforcement for a specific structural application is a complicated problem and is related to other factors including magnitude and type of loads, fabrication methods, service environment, required service life, strength and stiffness required, and economic considerations.

Tancreto and Haynes have concluded, based on their studies of the flexural behavior of ferro-cement with various sizes of woven wire mesh reinforcement, that the best overall compromise for strength, workability, and cost was a 1/4-inch by 1/4-inch mesh of 23-gage wire.¹⁴ However, comprehensive data for all types of loading and reinforcement are not yet available. Therefore, a detailed reinforcement optimization study in conjunction with a mortar mix design study is recommended for any major ferro-cement structures.

C. PERFORMANCE CHARACTERISTICS

The following sections contain discussions of various ferro-cement characteristics which are generally independent of strength properties. These include surface finish, durability, acoustical and fire resistance characteristics, repairability, dimensional stability, and maintenance.

1. Surface Characteristics

The surface characteristics obtainable in ferro-cement construction are similar to those for reinforced concrete or precast concrete construction. Surface control can be achieved for just about any level of accuracy through special fabrication methods, such as precision molds. Almost any degree of surface smoothness can be achieved by treatment of the molds or by finishing techniques. In addition, mortar additives and surface coatings can be used to improve smoothness and durability.

Using present mechanical or hand finishing techniques for concrete floor slabs, surface textures ranging from very rough or skid resistant

to extremely smooth can be obtained. By using smooth molds and vibration during placing, surface texture on the contact surface can be made hard and smooth.

Surface durability is largely dependent on the quality of the mortar. Reports by the Portland Cement Association²⁴ and the American Concrete Institute²⁵ on the wear resistance of Portland cement concrete show that compressive strength is the most important single factor related to wear. These studies show a relationship between increased concrete compressive strength and increased abrasion wear resistance. A similar relationship was observed for mortar, although abrasion wear resistance of mortar was found to be less than that of concrete with large aggregate. Wear resistance of concrete and mortar is also enhanced as cement content is increased and water-to-cement ratio is decreased. Both of these factors help to make the mortar matrix more dense and favor the wear resistance of ferro-cement mortars that are characteristically cement-rich and low in water content.

Surface durability of concrete and also of ferro-cement is dependent on finishing and curing. Excess surface moisture and rapid loss of surface moisture must be avoided. These conditions can be met within the scope of normal concrete technology. Epoxy coatings and marine paints have been used on ferro-cement boat hulls for added corrosion protection and surface durability. Coatings of this type could add significantly to costs, yet their use may be required in certain applications. The need for surface coatings is further discussed in the section on corrosion resistance.

Studies conducted in 1970 at MIT by S. A. Frondistou-Yannas and S. P. Shah²⁶ show that the addition of polymer latex additives to ferro-cement mortar result in higher extensibility and greater toughness. These results imply that wear resistance could be enhanced by the use of this type of additive in ferro-cement mortars. However, Frondistou-

Yannas and Shah show that the addition of polymer latex additives to ferro-cement mortar result in higher extensibility and greater toughness. These results imply that wear resistance could be enhanced by the use of this type of additive in ferro-cement mortars. However, Frondistou-Yannas and Shah observed that polymer latex additives had the detrimental effect of causing more shrinkage; thus this area warrants further study.

Although no data exist on the effects of high-velocity winds, such as occur in wind tunnel structures, Portland Cement Association studies²⁴ of hydraulic abrasion and cavitation show that good quality concrete is not affected by a steady, tangential, high-velocity flow of water. The long-term behavior, however, of plain and polymer latex-added or epoxy coated ferro-cement mortars in wind tunnel environments should be studied. A preliminary evaluation of the effects of high-velocity air flow on ferro-cement was conducted in the test program described in this report. Findings are discussed in Chapter IV.

2. Corrosion Resistance

Factors affecting ferro-cement durability and methods for improving it are discussed in this section. Factors related to corrosion and corrosion resistance of ferro-cement can be obtained from sources within the concrete industry. Information about concrete durability, concrete protection, and the use of admixtures relative to corrosion resistance is included in the reports of ACI Committee 201,²⁵ ACI Committee 515,²⁷ and ACI Committee 212,²⁸ respectively.

Deterioration of reinforced concrete (and ferro-cement) in corrosive environments generally results from chemical attack on the concrete and corrosion of the steel reinforcement. The extent of chemical attack on concrete is mainly related to its permeability, its alkalinity, and the tendency of hydrated cement compounds to undergo undesirable chemical reactions such as sulfate reactions. Penetration of fluids

into concrete can cause adverse chemical reactions with the cement, aggregate or steel. Corrosion of steel reinforcement in concrete results primarily from penetration of corrosive agents through cracks in the concrete covering, and deterioration of the concrete cover. The degree of protection given reinforcement by the concrete cover is dependent on the concrete quality and depth of cover.

Susceptibility of ferro-cement to deterioration from corrosive elements is primarily related to reinforcement cover, which is typically quite thin (about 1/8 inch) compared to ordinary reinforced concrete, and therefore provides less protection to the reinforcement. This problem has generally been treated by the following measures: (a) Increasing impermeability of mortar by low water-to-cement ratio, and careful attention to proper proportioning, grading, mixing, placing, and curing; (b) Application of impermeable coatings; (c) Added protection to the reinforcement such as galvanizing; and (d) Proper design to eliminate or minimize the extent and width of mortar cracks. A qualitative relationship between crack width and corrosion resistance, established by Walkus and Kowalski,⁶ is shown in Figure 3. In general, dealing with the susceptibility to corrosive attack resulting from the thin ferro-cement section and reinforcement cover requires high quality materials for the mortar and a high degree of control in mixing and placing.

The need for protective coatings is based on the specific structural application. The following two general conditions exist relative to corrosion resistance for reinforced concrete and ferro-cement:²⁵

1. Those in which proper attention to the concrete itself will provide immunity or an acceptably low rate of deterioration, and
2. Those in which it is necessary to prevent contact between the corrosive chemical and the concrete by means of a protective coating.

Concrete and mortar specifications that assure resistivity to many corrosive elements are well within the state-of-the-art in concrete technology. For important or unusual uses of ferro-cement, however, especially in view of the thin reinforcement coverage, new specifications should be developed that include tests to determine adequacy of corrosion resistance. In case of inadequacy, protective coatings may be desirable. Experience with ferro-cement in marine construction has shown that application of impervious coatings is required in most cases.

Protective coatings that have been used in marine ferro-cement construction are primarily resin-based coatings such as polyester, urethane, and epoxy. Desirable qualities for coatings include low cost, ease of application, impermeability, chemical resistivity, extensibility, and toughness. Careful preparation is necessary for applications of these coatings. A significant problem, especially in amateur-built ferro-cement boats, has been debonding of protective coatings.

Additives have been used in ferro-cement mortar to obtain greater density and hence greater corrosion resistance. One commercial boat building company employing ferro-cement is currently using an acrylic latex additive with apparent success.²⁹ The outside (or gel) coat of mortar contains the acrylic latex additive while the remainder of the cross section uses regular mortar. Experiments conducted at MIT²⁶ showed that polymer latex additives produce mortar of increased toughness and extensibility, although increased drying shrinkage resulted. Based on these findings and the above mentioned use in boats, the use of a polymer latex added gel-coat appears very promising for many kinds of ferro-cement construction. The expense of applying a protective coating could be eliminated as well as the possibility of its debonding. This area should be carefully considered in future ferro-cement studies.

Studies of the effect of freeze-thaw cycles on ferro-cement samples conducted by A. M. Kelly and T. W. Mouat³⁰ are shown in Figure 14.

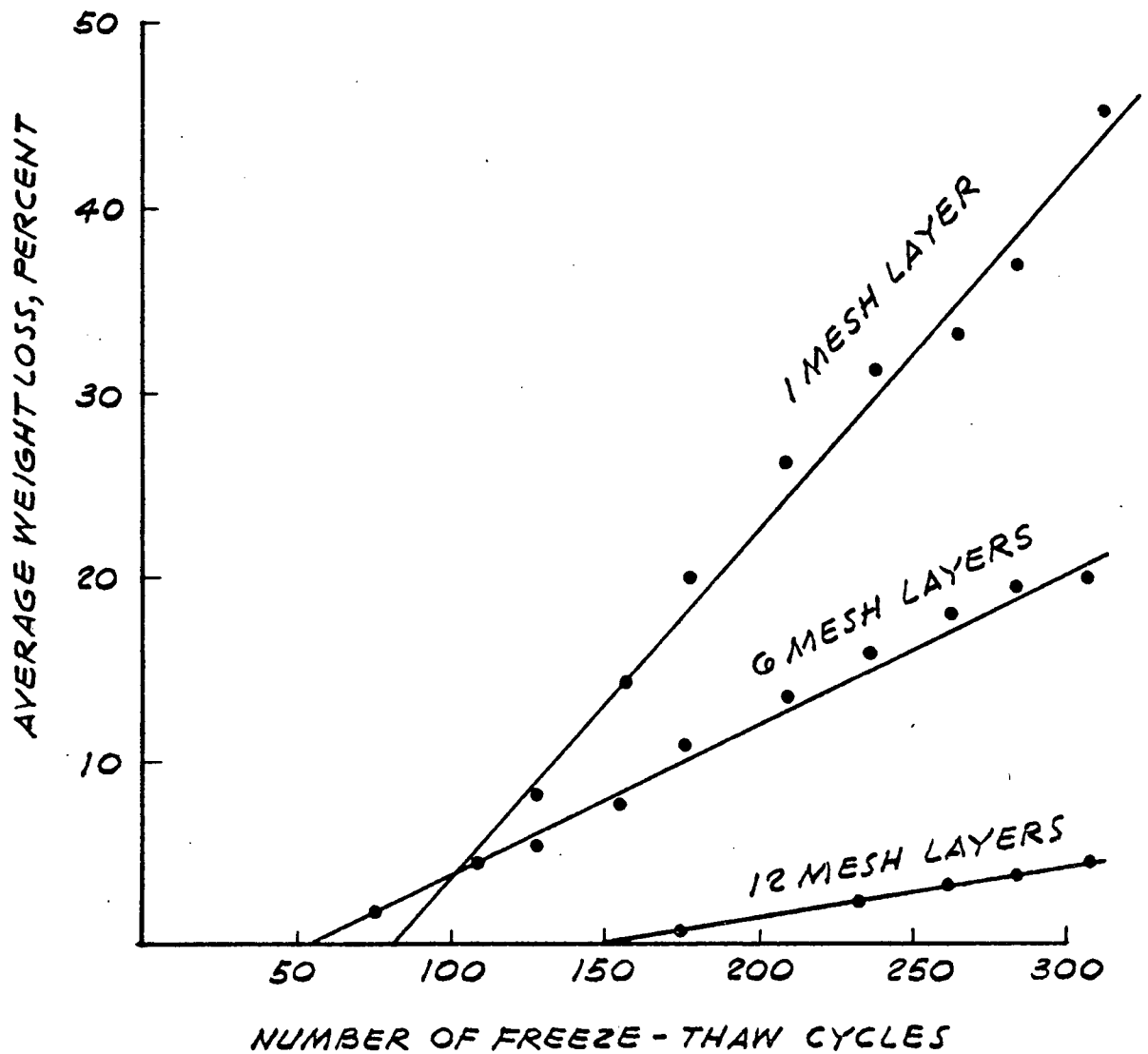


FIGURE 14 - FREEZE - THAW CYCLE TESTS
(FROM REF. 30)

These tests were conducted in accordance with ASTM C 291-67 (Method of Test for Resistance of Concrete Specimens to Rapid Freezing in Air and Thawing in Water) on 3/4-inch ferro-cement specimens of three types containing one, six, and twelve layers of mesh. The beneficial effect of adequate reinforcement is evident from these tests. It should be noted that the test procedure for ASTM C 291 is generally more severe than freeze-thaw cycles in actual structures.

Ferro-cement corrosion resistance is an important area for future study. Experience with ferro-cement marine craft shows that resistance to a corrosive sea water environment can be obtained. However, various forms of protective coatings are required for this. Because this corrosion protection adds significantly to costs, the economic feasibility of some proposed ferro-cement structures can be affected. Comparative studies of corrosion resistance for various types of ferro-cement, in conjunction with mortar mix and reinforcement studies are recommended in relation to specific structural applications.

3. Vibration and Acoustical Characteristics

No test results on vibration and damping of ferro-cement have been reported at present. It is expected that vibration characteristics would be approximated by the law of mixture of composite materials similar to Shah's results for modulus of elasticity. Vibration and damping have been studied in the test program described in this report and are discussed in Chapter IV.

Although no tests on the acoustical properties of ferro-cement have been reported, approximations can be made based on work with concrete. Figure 15 shows the sound-transmission loss through dense concrete and steel based on an approximate design method described by I. L. Ver and C. I. Holmer.³¹ It can be seen that 5/8-inch and 1-inch thick dense concrete exhibit greater attenuation than 1/8-inch and 3/8-inch steel plate over some portions of the sound frequency range. These results

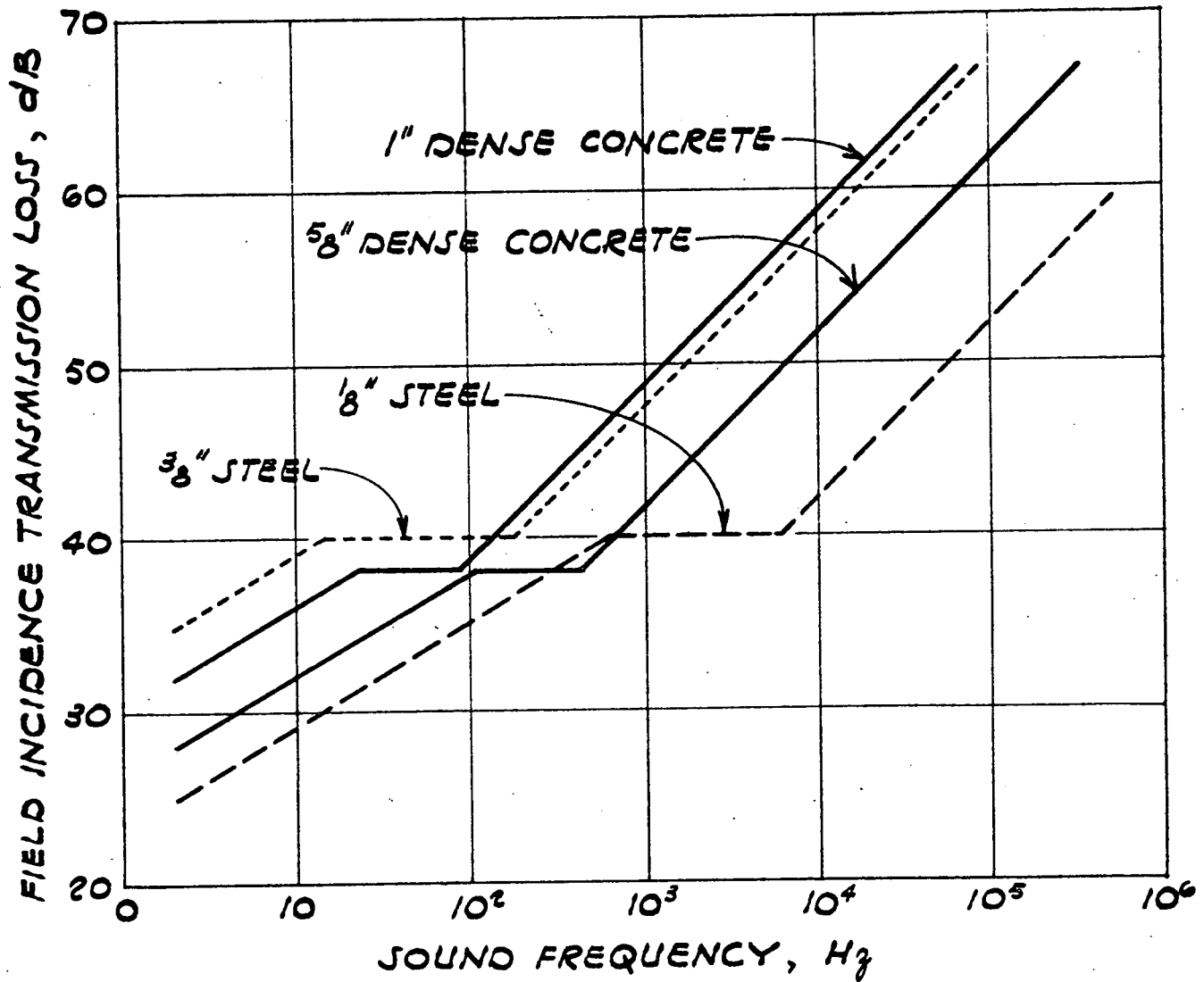


FIGURE 15 - SOUND-TRANSMISSION LOSS FOR
DENSE CONCRETE (FERRO-CEMENT) VS. STEEL
(FROM REF. 31)

give an approximate comparison between steel and ferro-cement with regular weight aggregate. However, conditions in an actual wind tunnel could vary. The acoustical properties of lightweight aggregate ferro-cement and those of ferro-cement with tensile or flexural cracks would probably vary from that of dense concrete. Comparative attenuation tests of various ferro-cement configurations in actual wind tunnel environments would be especially significant.

4. Fire Resistance

Ferro-cement has high fire resistance because the cement mortar is not combustible and provides insulation for the steel reinforcement. Tests conducted by Windboats, Ltd., of England in 1963 indicate that "test panels have withstood 1700° C for 1-1/2 hours with no effect on the material."¹⁸ However, heat does have a certain deleterious effect on cementitious materials and in addition, the 1/16-to 1/8-inch reinforcement coverage typical of ferro-cement is well below the minimum coverage required in reinforced concrete structures. These factors should be considered in experimental work to establish a fire rating for various ferro-cement configurations.

5. Repairability

The lower impact resistance of ferro-cement relative to fiber reinforced plastic and most metals is offset to a large extent by its ease of repair. Literature on ferro-cement marine craft contains a number of accounts of repair of severe impact damage within a few hours at nominal cost either in port or under way. Procedures for ferro-cement repair are similar to those for concrete and can be obtained from sources within the concrete industry such as the American Concrete Institute Manual of Concrete Practice.³² Typical repair materials are Portland cement mortar, epoxy grout, or commercial patching mixtures. Repair procedures involve removing damaged or spalled mortar, straightening or replacing deformed reinforcement, treating broken surfaces with an etching or bonding agent, and applying new mortar or patching material.

Repair of ferro-cement adversely affected by corrosion or fire would be done in a similar manner.

Tests conducted in 1970 by A. M. Greenius and W. N. English³³ for the Canadian Department of the Environment evaluated the strength of various ferro-cement repair materials. One-inch thick ferro-cement panels were tested to failure under flexural and impact loadings, repaired with one of several patching materials and then retested to failure. Patching materials used were Portland cement mortar consisting of one part cement, two parts sand and 0.4 parts water by weight; a commercial epoxy marine patching compound; and a commercial epoxy floor patching material.

Test samples repaired with Portland cement mortar were retested after 21 days curing time. Samples that had suffered reinforcement damage during original failure retested at 50 percent to 70 percent of their original strength. Other samples retested at about 80 percent of their original strength.

Test samples repaired with epoxy materials were retested after 7 days and regained virtually all their original strength. The repair with epoxy was affected by forcing the patching material into the cracks produced by initial failure, rather than chipping away damaged material as in the case of the repairs using Portland cement mortar. On re-testing, failure occurred away from the epoxy repaired cracks.

6. Dimensional Stability

The primary factors influencing structural dimensions and tolerances are drying shrinkage and creep. Drying shrinkage can be minimized by proper mix design and is a relatively short-term phenomenon. When a structure is cast in segments it can generally be compensated for by casting the segments slightly oversize. In the case of cast-in-place ferro-cement used in conjunction with precast concrete ribs, special

care should be taken to minimize shrinkage which results in internal stress build-up.

Ferro-cement creep has been studied in testing work reported by the Naval Ships Research and Development Center.¹⁹ The results are shown in Figure 16 and are for 1/2-inch ferro-cement specimens containing 6.2 percent galvanized wire mesh and loaded in flexure. The report of this work showed that from the nature of the log-log plot of the data that the ferro-cement samples tested have "the creep characteristics of a metal and not those of a composite."¹⁹ The data shown in Figure 16 are for a limited time duration. For structures with large dead loads or operational loads, creep data over a more extended time period are needed.

As in concrete construction, the use of prestressing in ferro-cement or in concrete ribs cast integrally with ferro-cement should be carefully studied from the point of view of dimensional changes caused by creep. Creep of prestressed members generally occurs over an extended period and can cause problems in the areas of joints and connections.

7. Maintenance

Maintenance of ferro-cement is discussed in this section, with reference to wind tunnel structures. Published data on long-term maintenance problems encountered in non-marine ferro-cement structures are not available. Long-term maintenance problems in ferro-cement marine craft are not well defined because almost all ferro-cement boats currently operating have been built since the mid-1960's.

The most important maintenance problem in ferro-cement boats is maintaining adequate protection against chemical (especially sulfate) attack. The prolonged exposure of ferro-cement boat hulls to sea water has generally required the use of protective coatings. Most failures of the coating material or of the hull itself have resulted

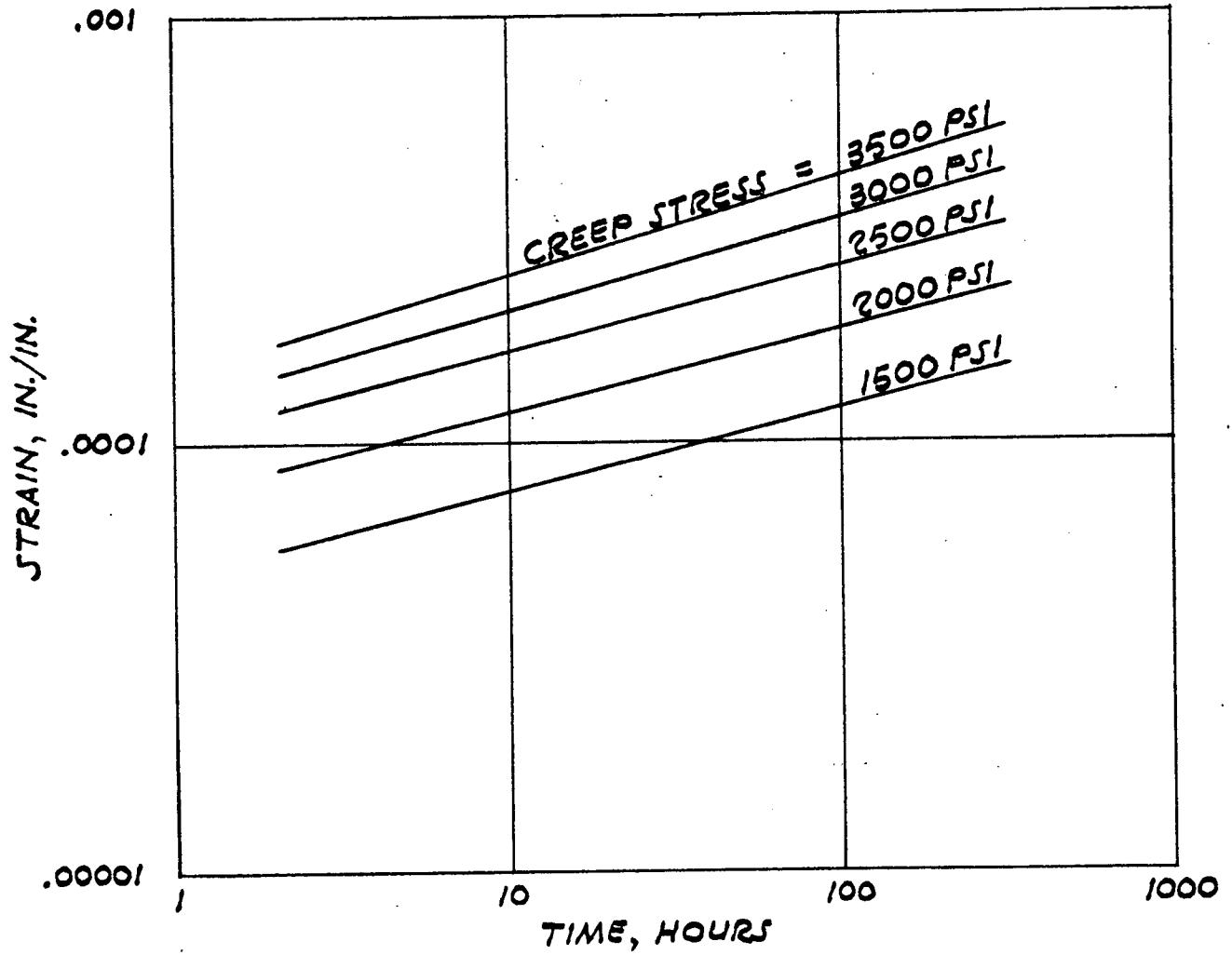


FIGURE 16 - FERRO-CEMENT CREEP TESTS
(FROM REF. 19)

from poor workmanship in obtaining good mortar penetration into the reinforcement and from poor selection of materials for reinforcement or coatings. Inadequate mortar penetration or high permeability have led to excessive deterioration from freeze-thaw cycles or sulfate attack.

Reinforcement configurations that allow excessive cracking have resulted in rapid sea water penetration and resulting deterioration. Some epoxy coating materials have been found to be inadequate. Coefficients of expansion for temperature and moisture change, which are much greater than that of the ferro-cement mortar, have led to shear failure in the mortar just under the coating. Debonding of the coating has occurred in many cases within 1-to 3-years.

Instances of failure and debonding of surface coatings in ferro-cement boats have been troublesome to repair, but experience has shown that such coating failures do not damage well-made ferro-cement hulls.²⁹ As previously discussed, in the absence of protective coatings the most important factor in obtaining ferro-cement resistance to chemical attack is high-quality mortar with low permeability.

Ferro-cement structures in atmospheric environments rather than sea water should be subjected to a much lower rate of chemical attack. Many structures -- with high-quality mortar, adequate reinforcement cover, and good design minimizing deflection and cracking -- can be used without coatings and be expected to require no maintenance.

Where moderate chemical attack is expected, such as from air pollution or engine exhaust residues, protective coatings may be required. Based on recommendations from persons currently engaged in ferro-cement research and construction,^{8,29} a good solution appears to be the use of a gel-coat of mortar with a polymer latex additive. This was previously discussed in the section pertaining to corrosion resistance.

The use of this gel-coat provides increased density and chemical resistance in the outer layer of the ferro-cement mortar and decreases the problems of debonding and mortar cracking. Although there are no long-term test results on the use of this gel-coat, based on the present state-of-the-art it appears to be the best way of providing a minimum maintenance ferro-cement structure for wind tunnel construction. Current and future research on protective coatings may produce improvements in the use of gel-coats and also other kinds of protective coatings.

Future ferro-cement test programs should include studies to verify the adequacy of the polymer latex additive gel-coat and studies to compare the basic properties and the effectiveness of various protective coatings. For wind tunnel structures subject to severe vibration loads, the current fatigue studies should be extended to determine the long-term effect on surface properties and maintenance problems.

D. CURRENT CONSTRUCTION METHODS

The following section constitutes the second part of the state-of-the-art study of ferro-cement where current construction methods were studied which can be applied to wind tunnel structures. The most common methods have been developed primarily for marine construction. These methods are adaptable for fabrication of other kinds of structures, including large wind tunnel structures. Of the commonly used construction methods, the two principal ones differ basically in the means by which the shape of the finished structure is formed and controlled. In the first method, structure shape is defined by a network of steel reinforcing bars which is overlain with wire mesh (Figure 1). The surface is controlled by hand placing and troweling of the mortar. The second method utilizes a mold to achieve the required finished shape and surface. The use of precisely constructed, reusable molds appears to be especially compatible with the structural and economic requirements of wind tunnel construction.

Ferro-cement construction using frames or networks of reinforcing bars for shape control is more labor-intensive and achieving close dimensional tolerance is more difficult. The cross section shown in Section 1a of Figure 1 is typical of one-unit, amateur-built private yacht construction where the cost of a mold for one unit is excessive and where labor time is not accounted. A large amount of labor is required for fabricating the reinforcing bar and wire mesh reinforcement network, placing the mortar to insure proper penetration, and trowel-finishing the mortar to the required dimensional precision.

The problem of dimensional tolerance can be greatly reduced by the use of molds. The use of molds also reduces labor in placing and finishing the mortar and generally requires less skilled workmen. Molds are currently being used in the construction of a large ferro-cement barge in Vancouver, British Columbia, and of large sailboat and motorboat hulls in West Sacramento, California. These two projects warrant further discussion because they involve several of the latest innovations in large-scale, commercial ferro-cement construction.

The construction of a 180-foot prototype ferro-cement cargo barge by FERROCON Industries, Ltd., Vancouver, British Columbia,⁴ has been partially sponsored by the government of Canada for the purpose of developing new Canadian technology. A large amount of research was conducted in connection with this project and the test data has been retained as proprietary information by FERROCON Industries. Discussions with David J. Seymour, Naval Architect,³⁴ who had complete design responsibility for the FERROCON barge project, indicate that some of the most advanced state-of-the-art procedures in ferro-cement design and construction were utilized. Precast, post-tensioned concrete ribs and frames were used in conjunction with cast-in-place ferro-cement shells for the hull and deck. The vessel was designed to comply with the standards of the American Bureau of Shipping for ocean-going barges. As an example of the strict specifications, a minimum modulus of rupture of 6000 psi was required for the hull and deck. Zero-slump

mortar and extensive vibration during placement of mortar were used to help meet this strength requirement. It is expected that most design requirements for civil engineering uses of ferro-cement will be below those encountered in this project.

The 55-foot motor and sailboat hulls being produced by Fibersteel Corporation, West Sacramento,²⁹ utilize a concrete cavity mold for the hull and deck and also a unique process for casting ferro-cement. By this process, a wet-mix spray gun is used to cover the surface of the cavity mold with a 1/16-inch gel-coat of ferro-cement mortar containing an acrylic latex emulsion additive. After this first coat has an initial set, a first layer of reinforcement is laid onto the mortar and a coat of ordinary mortar is sprayed on. A second layer of reinforcement is then placed before the mortar sets and the sequence is continued until the required thickness is reached. Some advantages of this method are good surface and dimensional control through the use of molds, excellent penetration of mortar into reinforcement mesh, hence good bond without the need for vibration and good adaptability for production line operations. Compared to the methods developed by FERROCON Industries this method uses a wetter, thus somewhat weaker, mortar mix and gives less accurate placement of reinforcement. However, for uses where load levels are relatively low and ease of construction becomes of primary importance, it appears that a process similar to this layering method would result in cost advantages.

A third significant ferro-cement project is currently being carried out by the Naval Ship Research and Development Center.⁵ This work involves research and prototype construction of 24-foot ferro-cement motor launches. Steel molds and hand application of mortar were used for construction of three prototypes. Minimum weight was important for these craft and hulls as thin as 3/8 inch were used. At least one prototype was successfully field tested for a year in sea conditions exceeding design requirements.

in the survey reported by Walkus and Kowalski,⁶ which is related primarily to current ferro-cement work in Eastern Europe, some interesting fabrication techniques are discussed. These techniques have been developed primarily for prefabricated curved or folded-plate roof elements and are referred to as "vibro-pressing" and "vibro-bending." They are described as follows:

Basically, "vibro-pressing" consists of a concrete dispenser moving on rails and following the profile of the element, the dispenser vibrating and pressing the mortar into the mesh fixed below it. "Vibro-bending" usually means that a ferro-cement sheet is cast flat on a steel mold which then has its sides raised to form finally a V-shape. The bending is accomplished through a small angle and to a relatively large radius so as to create the least disturbance for the parts already cast. Another variation of this technique consists of "winding" a ferro-cement sheet on a circular former so as to produce a trough element. The process may also be accompanied by mold vibration.⁶

Material and fabrication costs for the large ferro-cement marine projects currently under way in the United States and Canada are difficult to evaluate because most are in preliminary or prototype stages where costs are not representative of final construction. The feasibility of ferro-cement for civil engineering structures is expected to depend heavily on the economy of fabrication. The application of ferro-cement to wind tunnel construction is discussed in Chapter V. In Chapter VI various cost factors related to this kind of construction are reviewed.

IV. FERRO-CEMENT TESTING PROGRAM

The review of published and unpublished data discussed in the preceding chapter indicated that in a number of areas insufficient information was available. A limited test program was therefore developed and conducted to obtain preliminary data about those parameters that could be important in wind tunnel construction. The ferro-cement characteristics tested are related to the high speed air flow and vibratory loading present under operational conditions in most wind tunnels and include: strength and cracking behavior under fatigue loading, vibration and damping properties, and resistance of ferro-cement surfaces to abrasion from high velocity air flow.

Inadequate performance in any of the above material characteristics could seriously limit the feasibility of ferro-cement for wind tunnel construction. Therefore, to improve the reliability of the conclusions reached in this report, tests were conducted to obtain preliminary data in these areas. The tests were designed to provide preliminary values of the material properties from which estimates as to the adequacy or inadequacy of the material could be made. In addition, some static tests in compression, tension, and flexure were conducted to provide a correlation between the properties of the test samples studied in this program and those studied by other investigators as described in the preceding chapter. The materials and procedures utilized in testing are described in Section A and the results are presented and discussed in Section B of this chapter.

A. DESCRIPTION OF TESTS

Criteria for the tests were developed by John A. Blume & Associates, Engineers. Test specimens were furnished to Dr. William J. Venuti, Professor of Civil Engineering, California State University, San Jose,

who conducted the tests. The tests were performed in the Advanced Structures Laboratory at the University. Appendix C contains a detailed report of the test equipment and experimental methods.

1. Test Samples

Two large ferro-cement panels were fabricated by Fibersteel Corporation, West Sacramento, using the layering process described in the preceding chapter. The panels were 3 feet by 5 feet by 1/2-inch thick and were made in accordance with the specifications listed in Table 1. The panels were cast on 3/4-inch concrete form plywood and after curing were cut into test samples. Figures 17a and 17b show the mortar spraying process and a layer of wire mesh placed into the wet mortar. The casting procedures and materials are the same as those used by Fibersteel in fabricating ferro-cement boat hulls, although they normally use expanded metal instead of wire mesh. Because of the fabrication procedures used test results should be representative of the properties obtainable in actual field-fabricated ferro-cement.

The panels were cured under a combination of steam and ambient temperature conditions. After curing a total of two weeks, panels were cut into test samples using an 8-inch diamond-blade concrete saw as shown in Figure 17c. The nominal dimensions of all test samples are shown in Table 1.

Nominal thickness of all ferro-cement samples was 1/2 inch, although actual thickness varied from about 0.470- to 0.600-inch. Variations in thickness were measured and the minimum thickness was assumed to control the load capacity of all test panels.

TABLE I

FERRO-CEMENT TEST SAMPLE DATA

MATERIAL SPECIFICATION

- Sand Del Monte White Sand, 30-mesh
- Cement Kaiser "Permanente", Type 1-2
- Reinforcement 5 layers 1/2 -inch x 1/2 -inch
x 19-gage welded wire mesh;
67,000 psi yield stress
- Additives none
- Sand/cement ratio 1.0
- Water/cement ratio 0.33

PHYSICAL MEASUREMENTS

- Nominal sample sizes (in inches)
 - mortar cubes 2 x 2 x 2
 - compression tests 4 x 6 x 1/2
 - tension tests 4 x 12 x 1/2
 - flexure tests 6 x 24 x 1/2
 - fatigue tests 6 x 24 x 1/2
 - vibration tests: (a) 6 x 24 x 1/2
 - (b) 6 x 24 x 1/2
 - (c) 6 x 36 x 1/2
 - air abrasion (affected area) 2 x 2
- Volume percentage of reinforcement
 (one direction only) 2.1 percent
- Specific surface of reinforcement
 (one direction only) 2.6 inch²/inch³



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FIGURE 17a

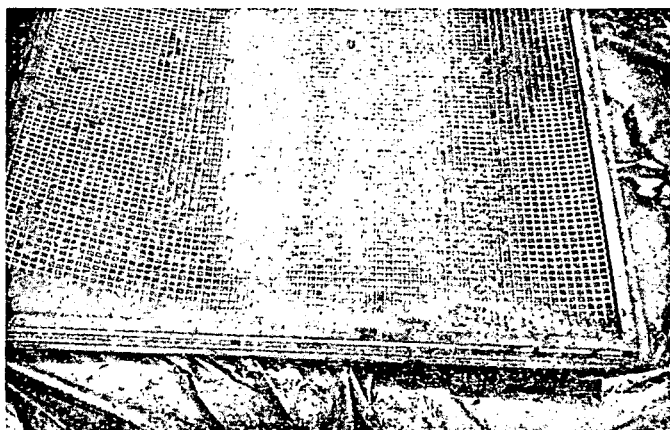


FIGURE 17b



FIGURE 17c

Some warping was observed in the panels and, therefore, a high-strength Hydrocal mixture was applied at the load and support regions of all samples. The Hydrocal was formed to ensure that all load and support points were in parallel planes.

2. Static Load Tests

Samples were tested to obtain static strength properties. These tests consisted of compression loading of mortar cubes and compression, shear, tension, and flexural loading of ferro-cement specimens. Material specifications and sizes of all samples are given in Table 1.

Mortar Cube Tests: Three mortar cubes were cast from the same batch as the test samples and tested in compression to ultimate load. Tests were conducted after a curing period of 6 weeks.

Panel Compression Tests: Three ferro-cement samples were loaded in the plane of the reinforcement and tested to ultimate compressive load.

Shear Tests: Several ferro-cement shear tests were performed. Analysis of the results indicated, however, that the mode of failure of the samples was flexure not shear. Therefore, these tests are not discussed further.

Tension Tests: Six ferro-cement samples were tested in tension to determine load at first crack and ultimate load. The stressed zone was 6 inches in length. Strips of conductive paint were applied to each face near the vertical edge. Leads from the paint strips were attached to an ohmmeter and the formation of the first crack in the ferro-cement and paint strip was detected by an increase in resistance. A tension sample in the test machine with the ohmmeter attached is shown in Figure 18a.



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FIGURE 18a

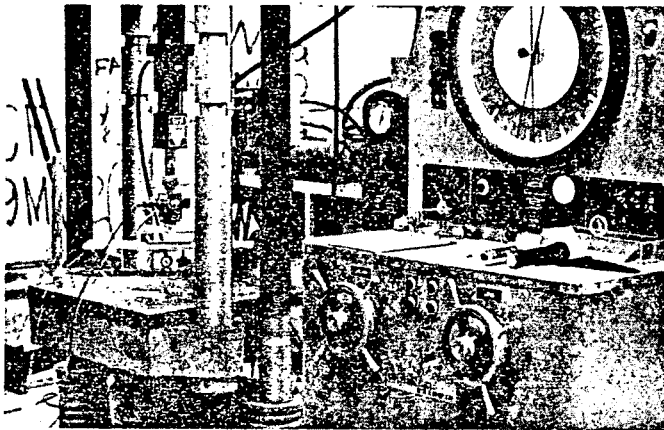


FIGURE 18b

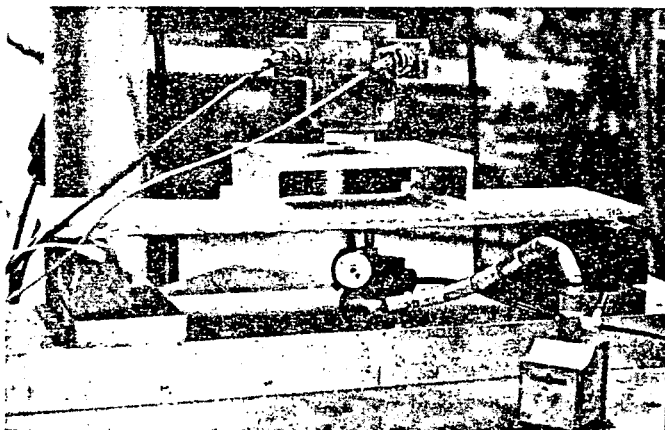


FIGURE 18c

Static Flexure Tests: Four samples were loaded in flexure to determine load-deflection behavior, first crack load, and ultimate load. Samples were loaded as simple beams with a 21-inch span; the load was applied through an aluminum channel section at two points 3.45 inches from the center of the sample. Load and deflection were plotted on a continuous chart recorder. Great care was taken to obtain the maximum degree of accuracy for the load-deflection records. The methods used are described in Appendix C. The occurrence of the first crack was detected by the sharp sound of mortar cracking.

3. Flexural Fatigue Tests

Repeated loading was applied to ten test samples using the same supports and loading device as the static flexural tests. Loading was varied between a minimum and maximum positive value and was controlled by a servo-operated hydraulic load cell. All tests were run for 1,000,000 cycles. Maximum load was constant for each cycle while deflection was permitted to vary. Load was applied at 12 cycles per second. Two strips of conductive paint were applied to the tension side to detect cracking of the ferro-cement. In addition, static load-deflection measurements were made on each test sample prior to fatigue testing, after 500,000 and after 1,000,000 cycles to evaluate any variations resulting from the effects of fatigue. The test frame, load cell, and a fatigue specimen are shown in Figures 18b and 18c. The deflectometer for static load-deflection measurements can be seen in Figure 18c.

4. Flexural Vibration Tests

Tests to determine vibrational characteristics of ferro-cement samples in flexure were performed on three samples using the same supports and loading device as the static flexure tests. A specified load value was applied and then suddenly released, allowing the beam to undergo free vibration. The displacement time-history

for each test was obtained from a linear voltage differential transformer positioned under the sample and permanently recorded using an oscilloscope and camera. Natural frequencies and displacement amplitudes were obtained from these records. Each sample was tested at several initial displacements with three replications for each displacement.

5. Air Abrasion Tests

A stream of high velocity air was directed over the surfaces of two test samples. The air flow was from a 1/2-inch air supply line and was adjusted to produce a pressure of 6 psi over a 2-inch by 2-inch area of the test samples for flow normal to the sample. The samples were then rotated so the air stream was 45 degrees from normal and the tests were continued for seven days. The surface affected by one test was on the side of the sample cast against the plywood form and the surface affected by the other test was trowel finished.

B. PRESENTATION AND DISCUSSION OF RESULTS

Results of the testing program are presented and the significant findings discussed in this section. These results are an important part of the following chapter wherein the state-of-the-art study and the testing program results are examined in evaluating the structural feasibility of ferro-cement for wind tunnel construction.

1. Static Load Tests

The results presented in Table II represent the average of samples for each type of test. The tension and flexure values for first cracking compare well with the test results presented in Figures 5a and 9. Load-deflection plots for two of the flexural tests are shown in Figures 19 and 20. The behavior recorded here is similar to that described by Walkus and Kowalski.⁶ The initial

TABLE II
SUMMARY OF STATIC TEST RESULTS

Test	Number of Tests	Average Crack Stress, psi	Average Ultimate Stress, psi
Mortar Cube	3	-	11,900 9,300 ^(a)
Compression	3	-	8,950
Tension	6	815 ^(b)	1,660
Flexure	4	1,320	5,120

(a) Equivalent 6-inch cylinder stress

(b) Based on paint crack

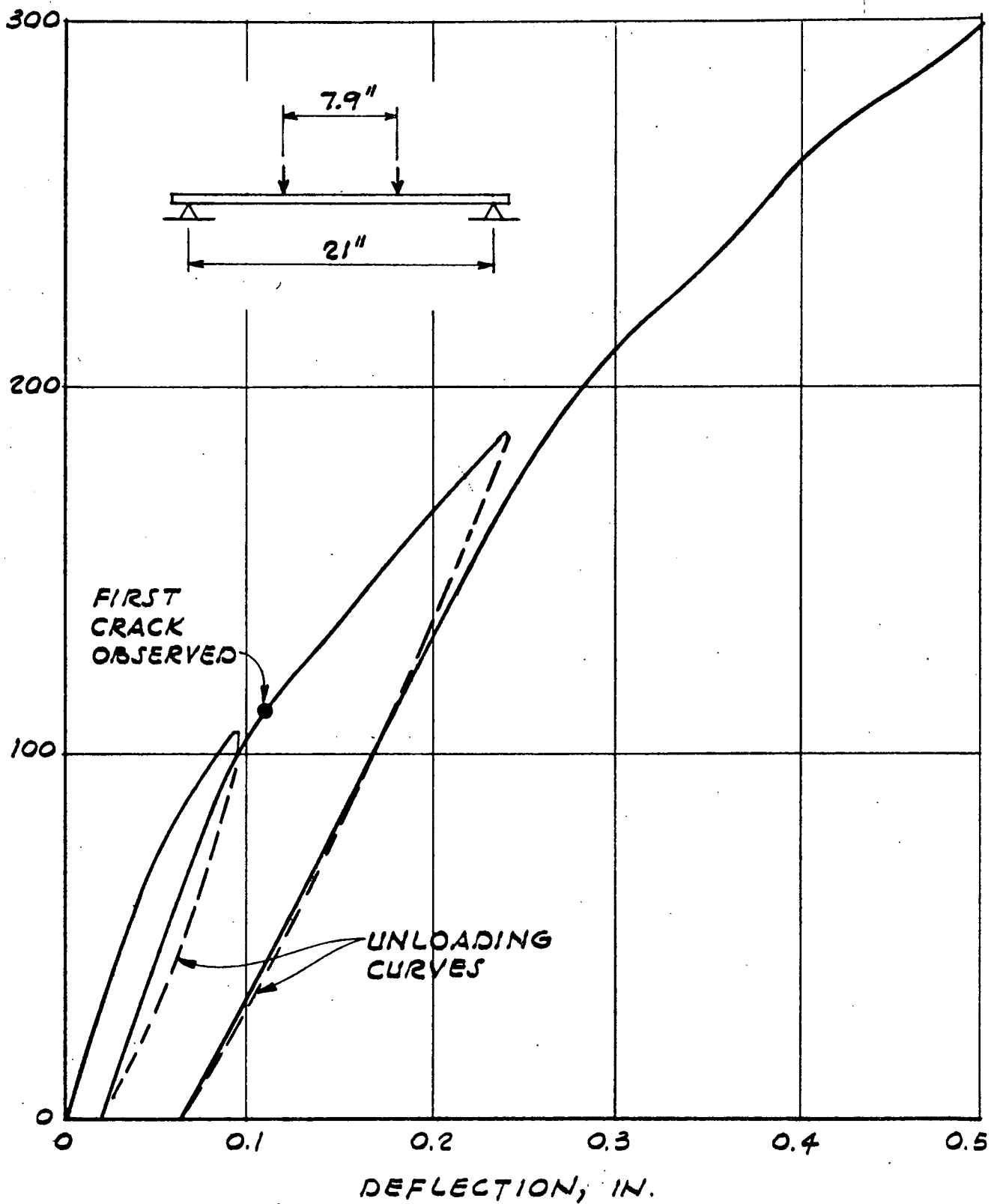


FIGURE 19 - STATIC FLEXURE TEST
SAMPLE #26

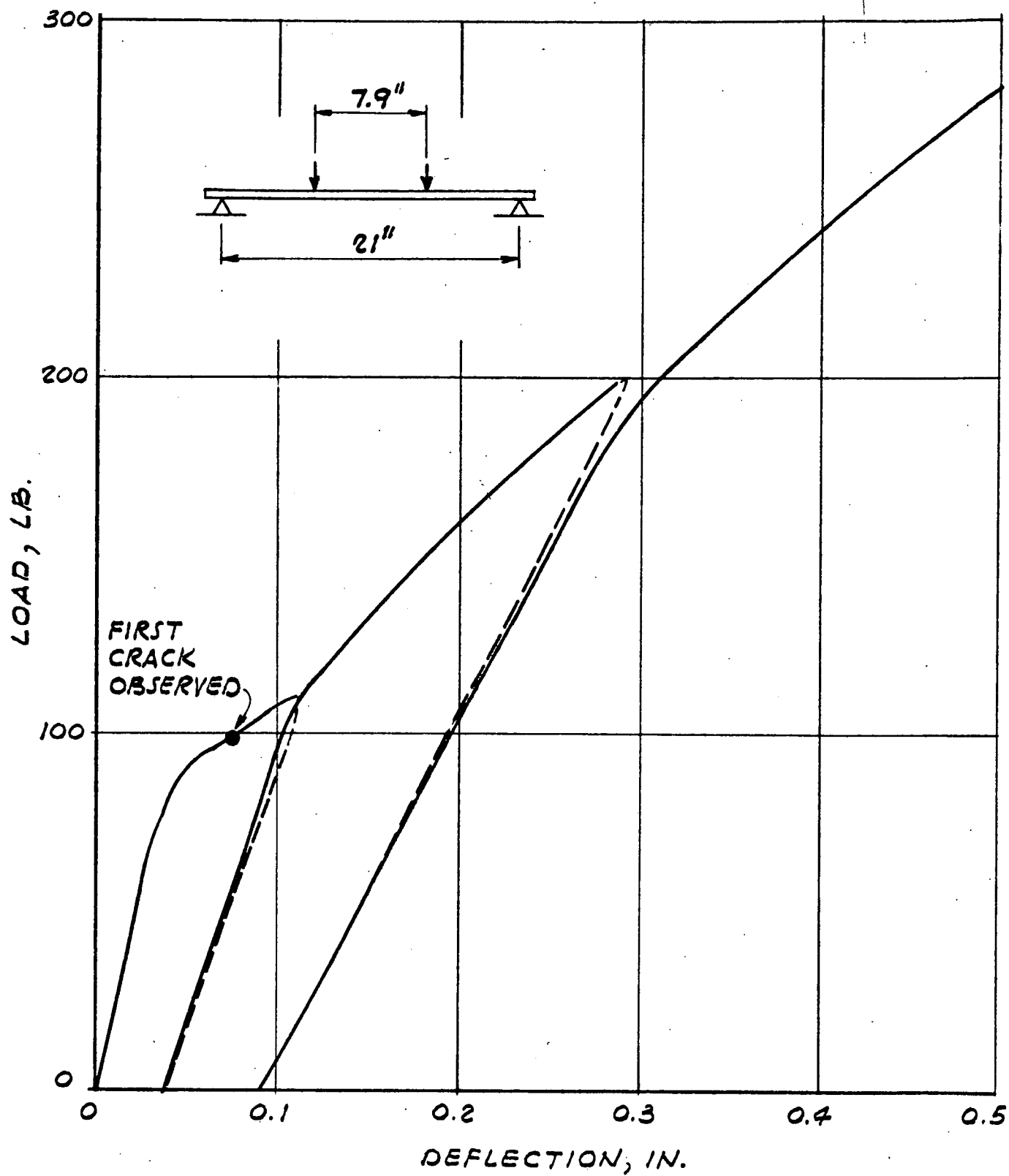


FIGURE 20-STATIC FLEXURE TEST
SAMPLE #3

linearly elastic behavior is followed by a region of quasi-elastic behavior and then by the occurrence of the first load-induced crack, which defines the upper limit of the effective elastic range of the material. The same behavior is expected in tension, although the tension tests did not include recordings of load-deflection behavior.

2. Flexural Fatigue Tests

The results of the fatigue tests are given in Table III. The second and third columns of Table III give the minimum and maximum ferro-cement stresses at the two extremes of the fatigue load range. These were held constant for each test. The fourth column of Table III shows the relationship between maximum stress for each test and the average cracking stress of 1320 psi obtained from the static flexure tests.

All tests were run to 1,000,000 cycles. Tests 1a and 1b were run on the same sample, so this sample was subjected to a total of 2,000,000 cycles at two different maximum stress levels. Tests 1 through 5 were run on samples assumed to be initially uncracked and no evidence of cracking was obtained from the conductive paint circuits during the tests. Tests 6 through 10 were loaded to cracking prior to fatigue testing so the fatigue behavior of a cracked section could be observed. The measurements of load-deflection behavior for each test sample, which were reduced to modulus of elasticity, were used to evaluate the results of fatigue loading on each sample. These data are given in the last three columns of Table III.

The measured values of elastic modulus for Tests 1 through 9 show no significant variation resulting from the fatigue loading. Although there is a slight trend in some tests toward decreased modulus with increased fatigue loading cycles, the trend does not

TABLE III FATIGUE TEST RESULTS

Test	Minimum Stress, psi	Maximum Stress, psi	Max. Stress 1320 psi	Measured E, psi x 10 ⁶		
				Before Fatigue Testing	At 500,000 Cycles	At 1,000,000 Cycles
1a	240	680	0.52	5.65	5.65	5.45
1b	240	830	0.63	4.92	5.01	5.01
2	240	830	0.63	7.70	6.85	6.50
3	240	830	0.63	3.40	3.15	3.22
4	240	1010	0.77	3.92	3.86	3.76
5	240	1180	0.90	6.25	6.90	6.60
6	240	1370	1.04	7.52 ^(a)	3.72	3.79
7	240	1470	1.11	4.71 ^(a)	3.38	3.24
8	240	1910	1.44	5.60 ^(a)	3.22	3.08
9	240	2230	1.70	5.87 ^(a)	3.03	2.70
10	240	3220	2.40	3.30 ^(a)	1.81	(b)

(a) Loaded to crack load before fatiguing; measured E is for initial slope-deflection curve (see Figures 19 and 20)

(b) Measurement impossible because of excessive deflection

appear to be strong. Test 10, however, shows a very significant deterioration from the fatigue loading. After 1,000,000 cycles load-deflection measurements could not be made because of excessive deflection. The stress level at which this test was run is comparable to that of the fatigue tests shown in Figure 12.

Measured values of elastic modulus compare well with previous measurements for cracked and uncracked sections. It should be noted that the samples for Tests 3, 4, and 10, assumed to be initially uncracked, appear to actually have been cracked, based on the measured values of modulus of elasticity.

These test results give a good indication of the fatigue behavior of ferro-cement sections of the type used for these tests and for similar fatigue loading. Tests using different materials and loading conditions will be needed to obtain a comprehensive picture of ferro-cement fatigue behavior.

3. Flexural Vibration Tests

Three samples were tested at varying initial deflections with three replications of each test. Results of the vibration tests are shown in Table IV. Tests were made on both uncracked and cracked samples. The condition of each sample prior to testing based on loading history and visual inspection is given in the second column of Table IV. The sample for the first series of tests was one that had been used previously for fatigue testing and was cracked and had experienced 1,000,000 cycles of fatigue loading at a maximum stress of 1,470 psi. A dead weight was attached at the center of the samples for some tests to prevent the sample from vibrating off the supports. The magnitude of this weight is given in the third column of Table IV.

TABLE IV VIBRATION TEST RESULTS

Tests	Condition	Weight W, lb	Measured Frequency, cps	Computed E, ⁶ psix10 ⁶	Measured Damping Ratio, percent		
					λ_{n+1}	λ_{n+3}	λ_{n+7}
I a	cracked;10 ⁶ fatigue cycles	50	17.7	3.55	4.1	3.3	2.7
I b	cracked;10 ⁶ fatigue cycles	50	16.8	3.19	7.1	5.6	4.0
I c	cracked;10 ⁶ fatigue cycles	100	12.2	3.27	4.9	4.4	3.5
II a	uncracked	15.5	30.3	5.17	2.8	2.6	2.2
II b	cracked	30	19.0	3.65	4.3	4.0	3.4
II c	cracked	45	15.0	3.32	5.8	4.9	4.2
III a	uncracked	0	23.2	5.32	3.6	3.3	3.2
III b	uncracked	0	22.6	5.15	3.0	3.1	3.0
III c	uncracked	16	12.8	5.35	3.4	3.3	2.8
III d	cracked	0	15.7	-	4.5	3.8	3.5

Typical examples of the photographic record of the amplitude time-history of vibration obtained for each test are shown in Figure 21. The average of vibration frequencies obtained from these records is shown in Table IV for each series of tests. From the frequency, weight, and dimensional properties of the samples, values of dynamic modulus of elasticity were computed and are shown in column 5. These values are comparable to measurements of static modulus of elasticity obtained from static tests. Average values are 3,400,000 psi and 5,250,000 psi for cracked and uncracked sections, respectively.

Initial irregularities in the amplitude of vibration were observed in most tests and can be seen in Figure 21. This appears to be the result of the samples leaving the supports because of vibration. Measurements of frequency and amplitude were made only in the portions of the records that exhibited a regular pattern of vibration.

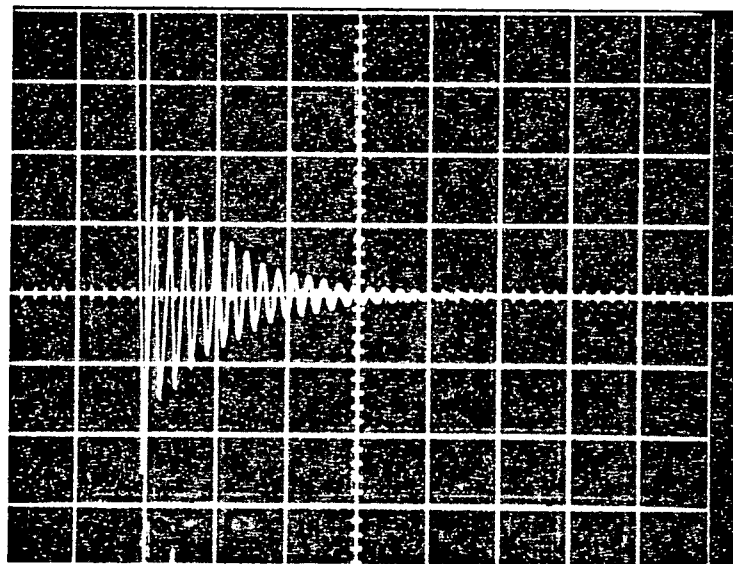
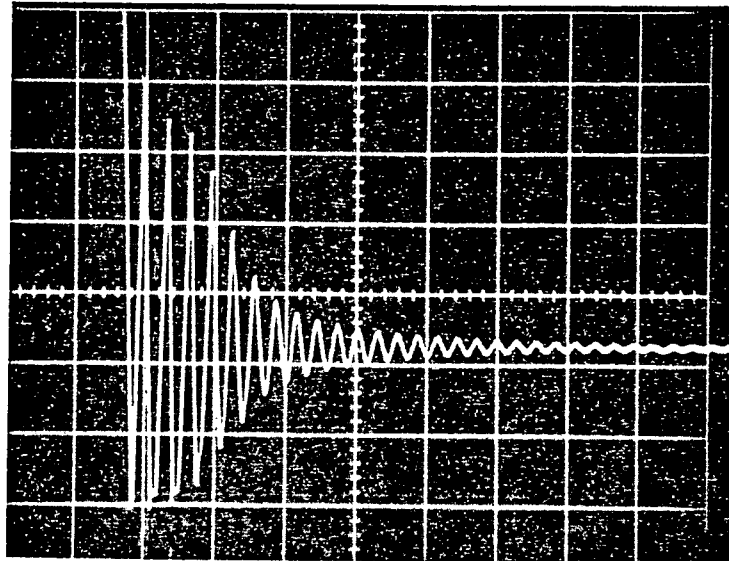
Amplitude measurements were used to estimate the internal damping of the ferro-cement specimens. Values of damping, λ , in terms of percentage of critical damping were computed from the following equation:

$$\lambda_{n+m} = \frac{100}{2\pi} \ln \left(\frac{u_n}{u_{n+m}} \right)$$

where

u_n = amplitude of nth cycle

u_{n+m} = amplitude of (n+m)th cycle



The nth cycle was chosen as the first cycle after irregular vibration ceased and was generally the 5th or 6th cycle. Values of damping were computed for 1 cycle, 3 cycles, and 7 cycles after the nth cycle and are given in Table IV. A difference in damping for cracked and uncracked sections is clearly seen from these results. Average values are 4.3 percent for cracked sections and 3.0 percent for uncracked sections. There appears to be a trend in the computed damping values toward decreased damping for the decreased amplitudes recorded in the 3rd and 7th cycles from the reference cycle. This trend is more pronounced for cracked sections than uncracked and indicates the possibility of a relationship between internal damping and amplitude of vibration.

4. Air Abrasion Tests

Qualitative evaluation of the surface of the two ferro-cement test samples indicated that no observable deterioration occurred during the tests. Observations were made visually and by touch and compared the tested surface area with untested surface area on the same test samples. These tests appeared severe based on observation of the tests in progress, but the results are not unusual in view of the high strength of the ferro-cement mortar used in the testing program.

V. FERRO-CEMENT FOR WIND TUNNEL CONSTRUCTION

The findings of Chapters III and IV were used to evaluate the possible use of ferro-cement for wind tunnel construction. The results of the state-of-the-art survey and the preliminary test program, which together provide a detailed picture of ferro-cement material properties and uses, were evaluated in terms of general applicability to wind tunnel construction. Based on the results of this evaluation, the performance requirements for a specific wind tunnel structure where the use of ferro-cement is proposed are presented. As ferro-cement material properties are generally compatible with these structural requirements, a scheme is outlined for the fabrication and erection of ferro-cement portions of this structure.

A. EVALUATION OF FERRO-CEMENT CHARACTERISTICS

The use of a material in a wind tunnel structure or in any kind of structure is primarily determined by whether the material can be economically designed to meet the requirements of the structure. In the following, the loading capacity of ferro-cement, as well as other material characteristics, is evaluated with respect to wind tunnel structures. General criteria for design of ferro-cement structures -- based on the state-of-the-art survey, testing program, and this evaluation -- are summarized in Appendix A. A detailed discussion of factors related to economy is contained in Chapter VI.

Proposed values of ferro-cement static design stresses are summarized in Table V. These values are based on the test results described in Chapter IV for 1/2-inch thick samples containing 5 layers of 1/2-inch by 1/2-inch by 19-gage welded wire mesh, which were fabricated using

TABLE V
PROPOSED FERRO-CEMENT DESIGN STRESSES

(Based on 1/2-inch thick samples with 5 layers of 1/2-inch by 1/2-inch
by 19-gage welded wire mesh)

Type	Criteria for Design Against Cracking	Design Stress Based Test Data For No Cracking
Uniaxial Compression	$0.25 f'_c \text{ (a)}$	2300 psi
Uniaxial Tension	$0.75 f_{t1} \text{ (b)}$	600 psi
Flexural Compression	$0.45 f'_c$	4200 psi
Flexural Tension	$0.75 f_{t2} \text{ (c)}$	1000 psi
Shear	$1.1 \sqrt{f'_c}$	100 psi

(a) f'_c = Ultimate mortar compression strength

(b) f_{t1} = Uniaxial tensile stress to produce first mortar crack

(c) f_{t2} = Flexural stress to produce first mortar crack

the layering process described in Chapter III. The design stresses in Table V are for an application where cracking is to be avoided. Thus the criteria for uniaxial and flexural tension are based on a reduction of the measured stresses at cracking. The remaining criteria are based on the recommendations of the ACI Building Code (ACI 318-63) for working stress design of concrete.

To meet the requirements of the latest ACI Building Code (ACI 318-71), which recognizes only ultimate strength design for reinforced concrete members, methods for estimating ferro-cement ultimate strength such as those proposed by Tancreto and Haynes¹⁴ for flexure could be used. Based on the first crack stresses reported in Chapter IV, it appears that a criterion based on limited cracking will generally govern the design.

The load capacities of a 5/8-inch and 1-1/8-inch ferro-cement shell, based on the design stresses in Table V, are given in Table VI. The capacities are also compared to that of an unstiffened 1/4-inch structural steel plate. It can be seen that relative tension and shear capacities are very low. Yet compression and flexural strength approach that of the steel plate of approximately equal weight. Also, flexural stiffness that is measured by the product of modulus of elasticity and moment of inertia (EI) is many times greater for the ferro-cement shells.

Based on comparisons given in Table VI, use of ferro-cement would be expected to result in lower tensile capacity compared to unstiffened steel of approximately equal weight. The low tensile and shear capacities may make ferro-cement use unfeasible for some structures; this can be partially offset by the use of reinforced concrete ribs.

The load-carrying capacity of ferro-cement is of first importance in most structural applications, yet other material characteristics can also affect its feasibility. Surface smoothness and durability obtainable in ferro-cement construction are generally compatible with wind tunnel

TABLE VI
COMPARATIVE FERRO-CEMENT AND STEEL LOAD CAPACITIES

Description	Ferro-cement ^(a) in Uncracked Condition (based on Table V)		Steel
	5/8-inch Shell	1-1/8-inch Shell	1/4-inch Shell
Weight ^(b) , psf	5.7	10.3	10.2
Compression, lb/in.	1440	2590	5000 (@ 20 ksi)
Tension, lb/in.	375	675	5500 (@ 22 ksi)
Shear, lb/in.	63	113	3620 (@ 14.5 ksi)
Flexure, in.-lb/in.	65	210	250 (@ 24 ksi)
EI ^(c) , in. ² -lb/in.	102,000	594,000	38,000

(a) Based on test data

(b) Lightweight ferro-cement mortar assumed

(c) Ferro-cement elastic modulus = 5.0×10^6 psi
Steel elastic modulus = 29×10^6 psi

requirements, although special surface treatment may be necessary in especially corrosive environments. Corrosion accelerated by mortar cracks is generally aggravated by the typically thin reinforcement cover. However, data relating cracking and crack width to design stresses and corrosion resistance, and also the use of protective coatings, provide methods for dealing with cracking.

The relatively high internal damping of ferro-cement together with its high flexural stiffness indicates that vibration problems should generally be minimized. Estimates of sound attenuation properties indicate that ferro-cement may be superior to a structurally equivalent steel plate over some portions of the sound frequency range. Within the range of available test data, fatigue strength of ferro-cement should not limit its use in most wind tunnel structures. Impact strength is relatively low, but there are a number of methods for improving it.

It should be possible to use ferro-cement in any structure where the foregoing strength and performance characteristics are compatible with the specific structural requirements. But the most advantageous use of the material appears to be in curved, thin-shell structures, which are difficult to form in other materials and that reduce ferro-cement stresses through a shape factor resulting from the curvature. The thinness of ferro-cement shells, however, accentuates the need for excellent workmanship and control in fabrication, particularly in maintaining the thin reinforcement cover and designing and placing the mortar so to minimize voids.

The overall feasibility of the use of ferro-cement must be based on its strength and performance characteristics as well as its relative cost for a specific structure. As noted previously, because of the labor intensive nature of ferro-cement construction, its economy is closely related to the development and use of automated or semi-automated production methods.

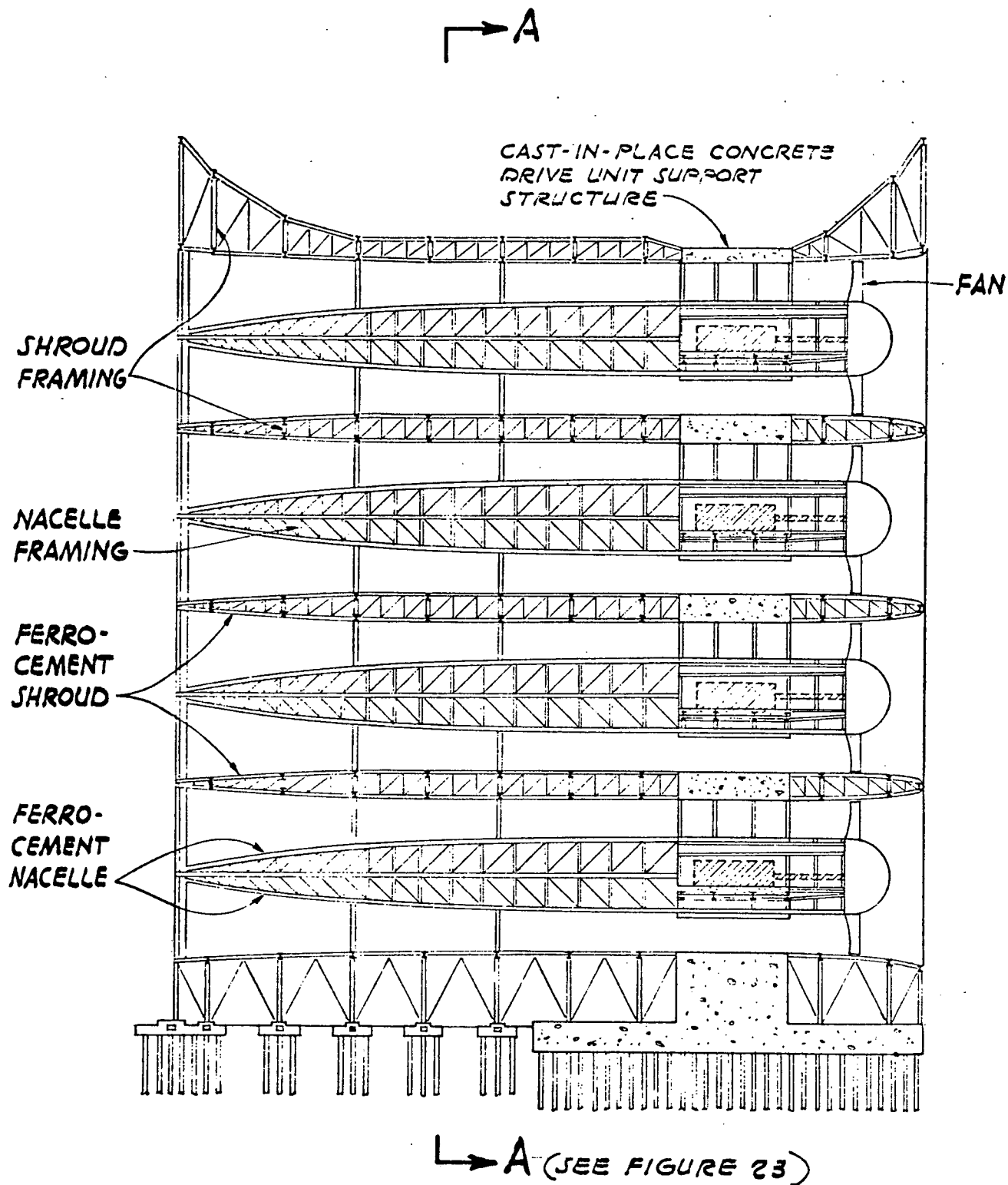
This is discussed in more detail in the cost study in Chapter VI. Performance requirements for a specific wind tunnel structure are outlined in the following paragraphs. A preliminary construction scheme is also presented based on these requirements, the evaluation for wind tunnel construction, and the preliminary design criteria in Appendix A.

B. TYPICAL PERFORMANCE REQUIREMENTS

The state-of-the-art survey, testing program, and structural evaluation of ferro-cement described in this report are directed toward the general applicability of ferro-cement to wind tunnel structures. The following discussion of performance requirements is based primarily on a specific Drive (or Power) Section for a large-scale subsonic wind tunnel such as that described in the March 22, 1971, John A. Blume & Associates, Engineers report "Conceptual Design Study of Power Section for a Proposed V/STOL Wind Tunnel." The ferro-cement portions of this structure are the shrouds and nacelles that require aerodynamic surfaces and are shown in Figures 22 and 23. The requirements outlined below are based on discussions with NASA Ames Research Center personnel as well as civil engineering practice as applied to typical large structures of this type.

Loading Capacity: Shrouds and nacelles must withstand all normal structural loads (dead, live, wind, seismic). Shrouds must resist a positive (inward acting) pressure of 90 psf at maximum wind tunnel speed. Structural materials must be capable of resisting the effects of vibration such as that caused by fan motor vibration or fan blade-induced pressure pulsing.

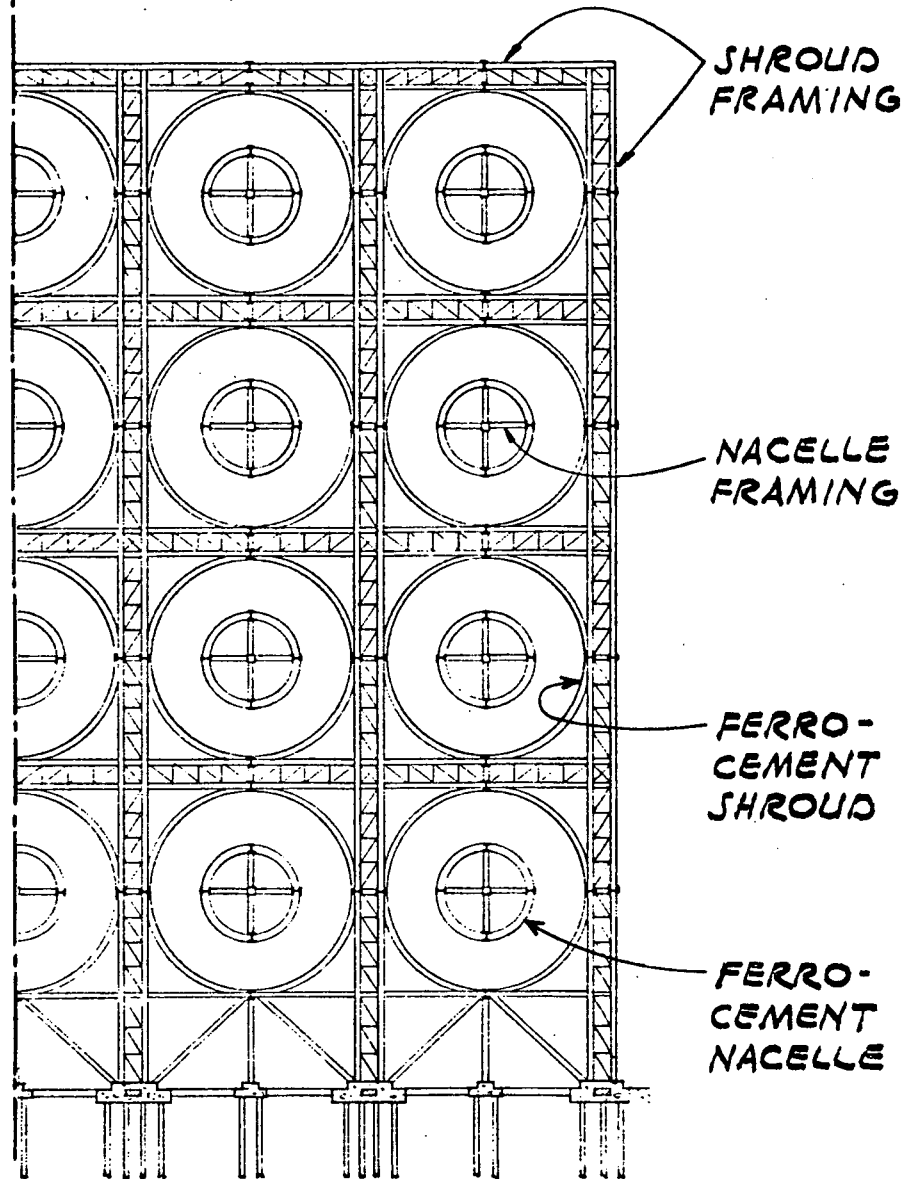
Structure Durability: All portions of the structure must retain their structural effectiveness over the required service life with normal maintenance.



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**FIGURE 22 - LONGITUDINAL SECTION THROUGH
PROPOSED WIND TUNNEL DRIVE SECTION**

SYM. ABT.
E



PARTIAL SECTION A-A

Surface Quality: Standard of reference for smoothness of aerodynamic surfaces is rolled steel plate. Surface finish should cause no more resistance to flow of air than rolled steel plate and must be capable of maintaining required surface smoothness under effects of maximum air speed. Air flowing in the tunnel normally contains no unusual substances except products of aircraft engine exhaust.

Dimensional Tolerance: Tolerances for deviations from nominal shroud and nacelle dimensions are as follows:

a. Offsets:

- within 20 feet of fan: none
- 20 feet to 40 feet from fan: $\leq 3/32$ inch
- greater than 40 feet from fan: $\leq 1/2$ inch

b. Deviation from "true" curve:

- within 20 feet of fan: $\leq 3/32$ inch from "true" surface;
0.2 degree maximum angle of departure from "true" line and surface
- greater than 20 feet from fan: not critical

Sound Attenuation: Standard of reference for acoustical output is existing 40-foot by 80-foot wind tunnel at Ames Research Center.

c. A PRELIMINARY CONSTRUCTION SCHEME

A scheme for fabrication and erection of ferro-cement shrouds and nacelles for the Drive Section shown in Figures 22 and 23 was developed and is described in the following paragraphs.

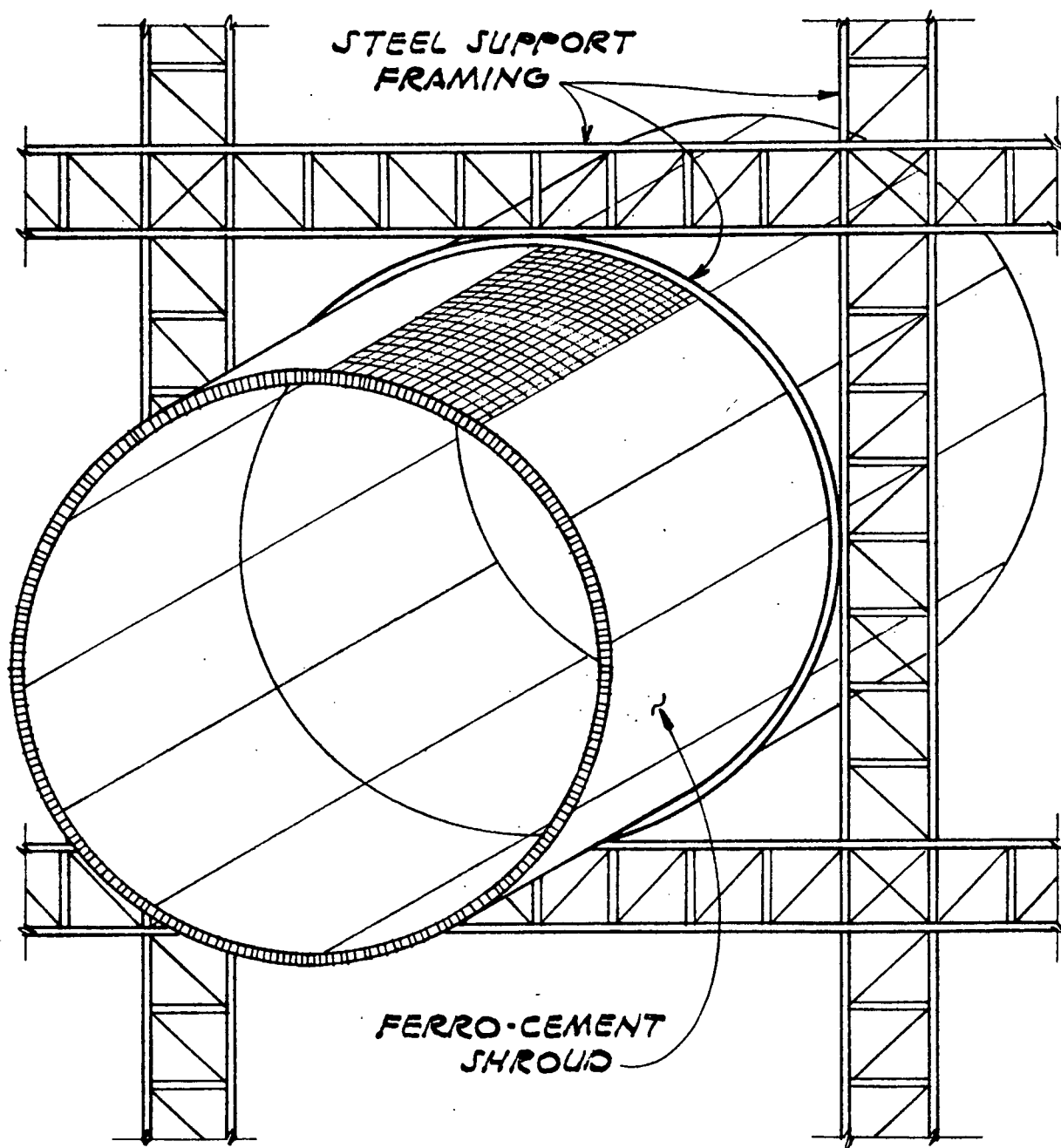
The construction scheme is based on the criteria presented in Appendix A and should meet the performance requirements outlined in the preceding text. In developing this scheme, materials or construction methods beyond the scope of the current ferro-cement state-of-the-art

or normal practices in reinforced concrete construction have been avoided. For the proposed structural usage, a ferro-cement design using readily available materials and proven construction methods is consistent with the feasibility and cost studies contained in this report.

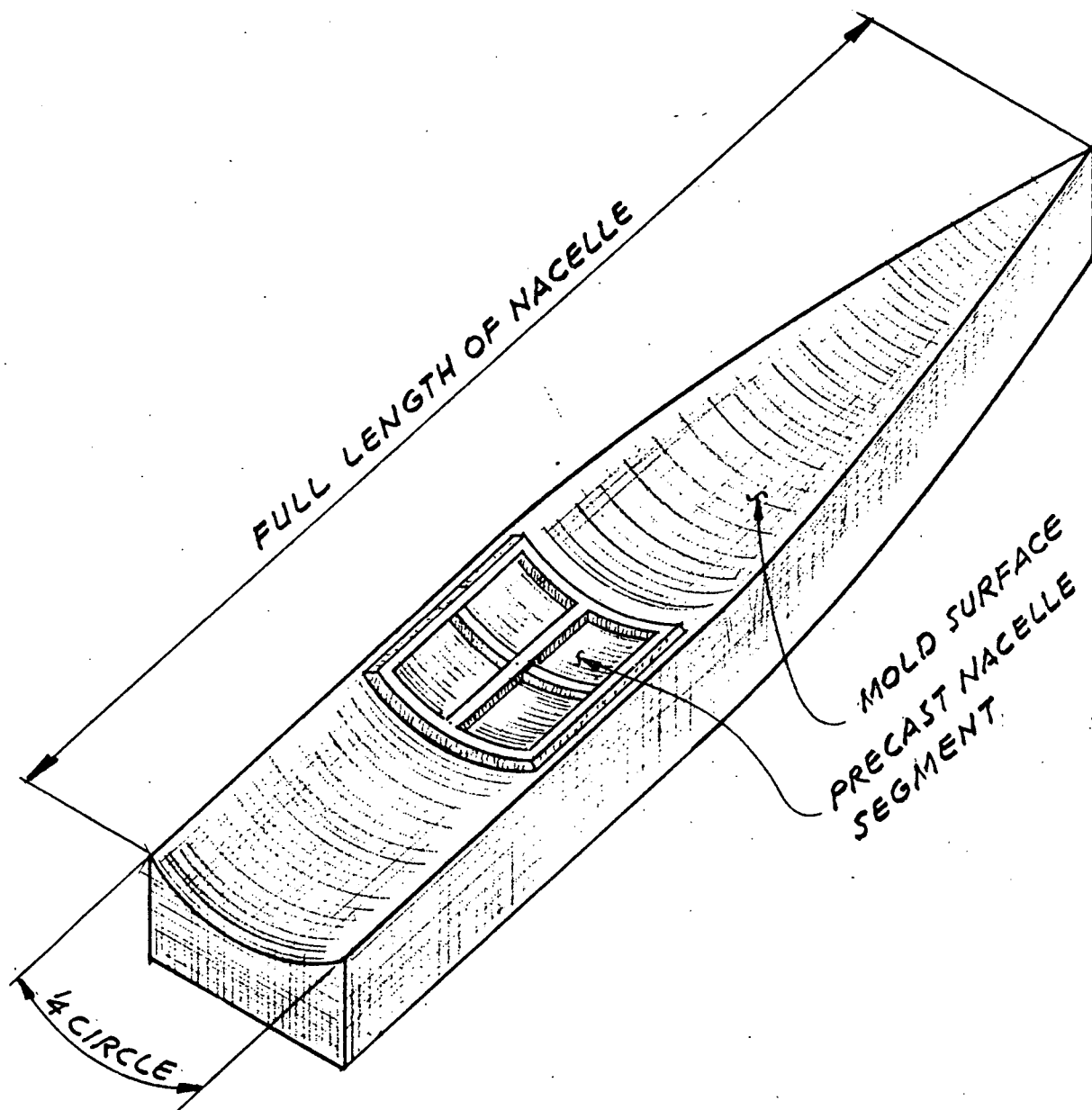
The structural and functional suitability of ferro-cement in the proposed Drive Section is based primarily on minimization of construction costs because load levels for this structure are relatively low. Thus, simplicity of fabrication is a significant design consideration. The previously described ferro-cement barge prototype being built in Vancouver by FERROCON Industries utilizes ferro-cement shells with yield strength in excess of 6,000 psi. However, this required hand placement of steel and mortar, hand vibration, and finishing using highly skilled workmen. For a project such as the wind tunnel shrouds and nacelles adequate strength could be achieved through a more automated, less costly fabrication process, similar to the layering process discussed in Chapter III.

Figure 24 is a partial isometric view of the Drive Section structure in Figures 22 and 23 and shows the relationship between the structural steel support framing and a ferro-cement shroud. The construction scheme consists basically of precasting the ferro-cement shroud (or nacelle) in segments and erecting and connecting the segments to a structural steel framework to form the finished structure. The cross-hatched portion of the ferro-cement shroud represents one precast segment. The completed shroud is constructed of many of these precast segments that are fabricated at ground level in reusable molds, then lifted and permanently fastened in place. The nacelles are constructed using the same procedure.

An isometric drawing of a nacelle mold is shown in Figure 25. The mold is the same length as the actual nacelle, but the width represents one-quarter of the nacelle circumference. Thus the mold is reused four



**FIGURE 24 - PARTIAL ISOMETRIC VIEW OF
SHROUD AND SUPPORT FRAMING**



times in casting the segments for one complete nacelle. The high re-use of molds for the entire structure is important to good economy in precast construction. The required dimensional control for the completed shroud or nacelle can be obtained by careful construction of the molds and using the surface in contact with the mold for the finished aerodynamic surface. Proper mortar mix design and curing procedures, consistent with the use of precasting, would be required.

The precast shroud and nacelle segments are lifted from the ground, positioned by cranes and connected together and to the supporting frame in a manner such as shown in Figure 26. Bolted connections are made to the structural steel framing. Shims can be placed between the shroud segment and steel framing ring to adjust the shroud dimensions to the required tolerances. Joints between segments are sealed with epoxy grout.

Figure 27 shows a typical precast shroud segment in isometric view. The segment is 20 feet long and spans between the structural steel support frames which are 20 feet apart. The segment is attached at its ends to a circumferential steel ring that is part of the support framing. The precast shroud segment shown in Figure 27 is designed to carry the design loads over a span of 20 feet in the manner of a flat plate. The shell thickness and size and spacing of longitudinal ribs are chosen to minimize the weight of the segment. Although not shown, a precast nacelle would be formed and supported in a similar fashion.

Design studies based on reinforced concrete practice and the state-of-the-art in ferro-cement, as well as the independent feasibility review presented in Appendix B, indicate that this construction scheme could be accomplished without major difficulties. Considerable additional design and testing work would, however, be necessary prior to initiating a project of this magnitude. Recommendations for additional ferro-cement research and development related to large-scale ferro-cement structures have been discussed in previous chapters of this report and are summarized in Chapter IX.

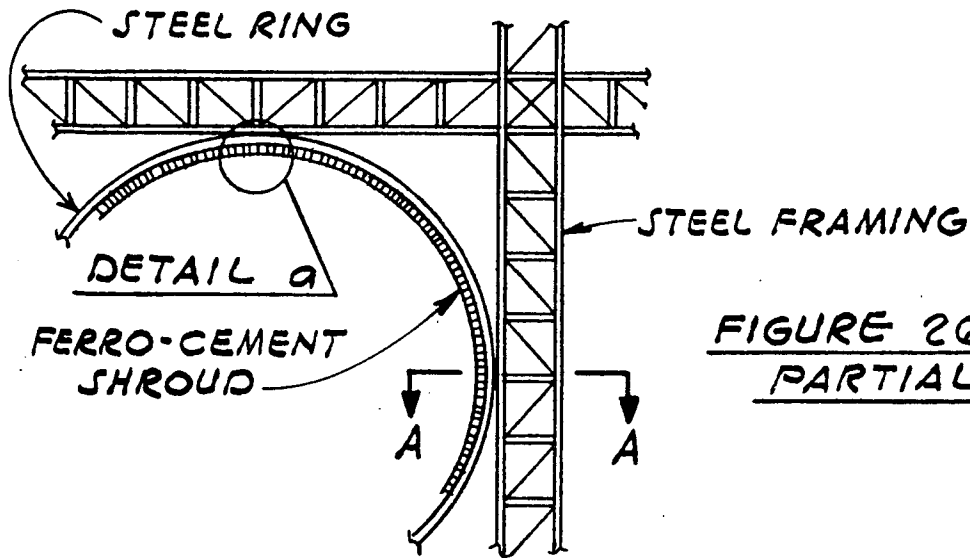


FIGURE 26a.
PARTIAL SECTION

FIGURE 26b.
DETAIL a

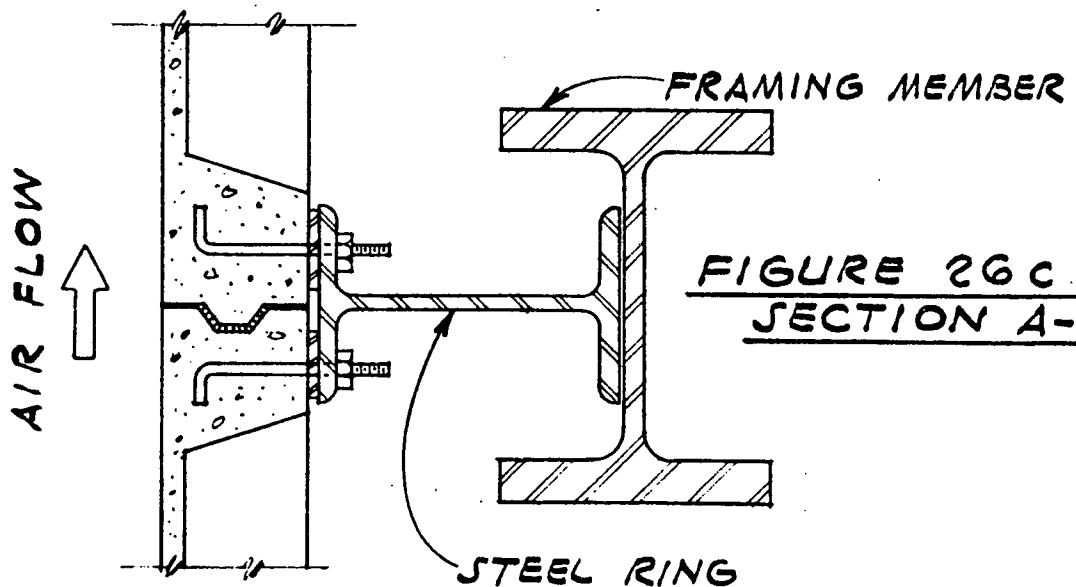
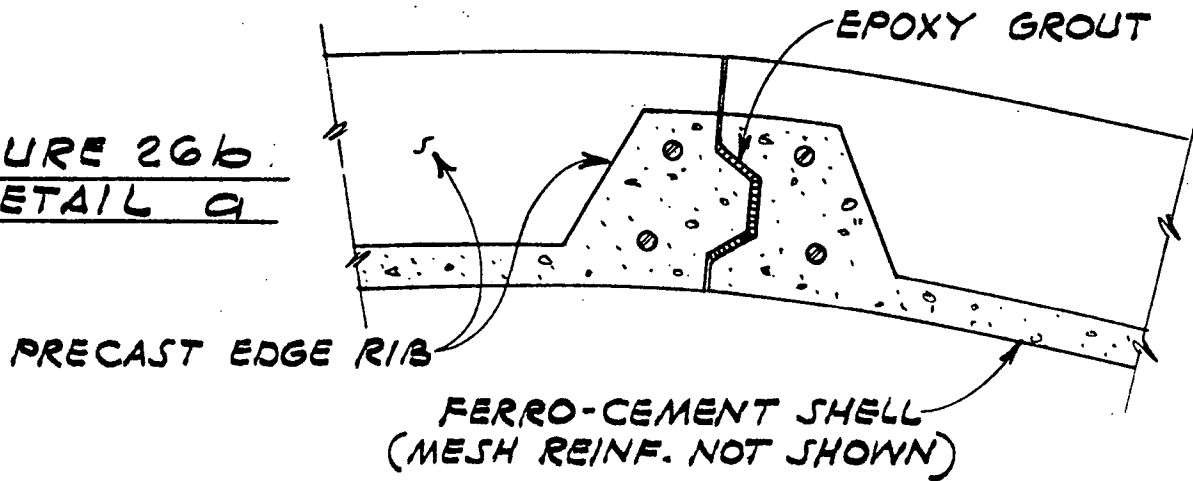


FIGURE 26c.
SECTION A-A

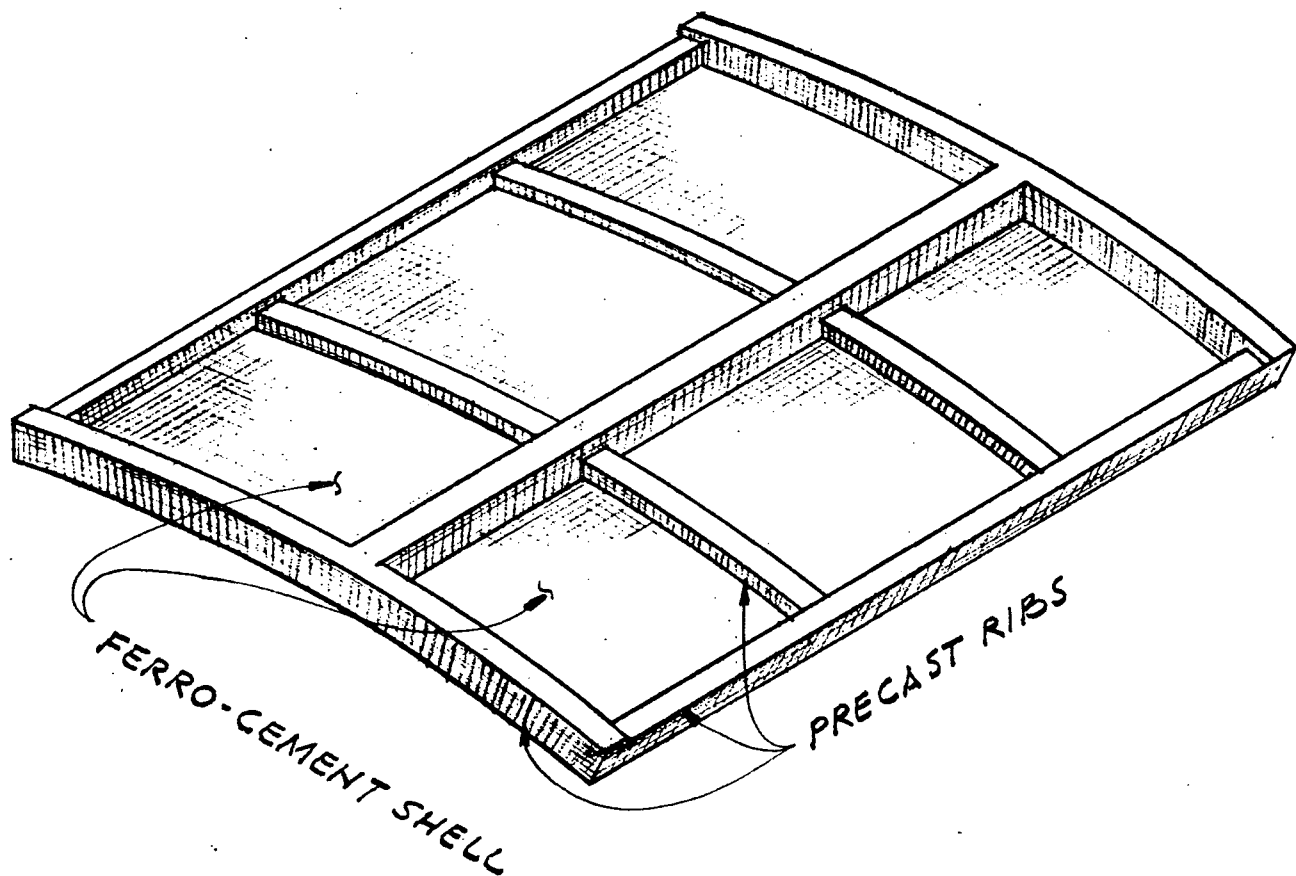


FIGURE 27- PRECAST FERRO-CEMENT
SHROUD SEGMENT

VI. COST STUDY OF FERRO-CEMENT FOR WIND TUNNEL CONSTRUCTION

Cost factors related to ferro-cement construction are discussed in this chapter. A comparison is made between relative costs for manual fabrication and more mechanized fabrication of a 55-foot boat hull. Using the preliminary construction scheme discussed in Chapter V, a cost estimate for the Drive Section shown in Figures 22 and 23 is developed. The unit costs used in this estimate are based on the recommendations of a consultant experienced in design and construction of a large ferro-cement marine project (Appendix B) and discussions with fabricators such as Fibersteel Corporation.

The cost factors important to ferro-cement construction include: cost of basic materials (sand, cement, additives, and reinforcement); cost of labor in producing the ferro-cement; cost of erection where in-place fabrication is not used; cost of special equipment such as precasting molds; and cost of special development and testing. Most construction methods now being used are very labor-intensive and sources of cost information concur that labor is the most significant cost factor in producing ferro-cement.

Because of this large labor factor, the use of labor-saving equipment and procedures are necessary for economical ferro-cement construction on a commercial basis. An example of the effect of mechanization comes from the boat-building industry. Based on an estimate from Jack R. Whitener,³⁵ a typical amateur-built 55-foot sailboat involves \$1,000 for materials and 1,800 to 2,000 man-hours for construction of the basic hull. This kind of construction involves manual layup of the steel reinforcing bar network and wire mesh followed by manual application and finishing of mortar. Compared to this are the techniques

used by Fibersteel Corporation that were discussed in Chapter III. Using a complete hull mold and a mortar spray gun with the layering process, this firm quotes a similar material cost, but only 100 man-hours of labor for completion of the basic hull.²⁶ The costs involved in this method would include amortization of the mold and special equipment, yet the labor savings result in substantial overall cost reduction.

As previously discussed ferro-cement construction for structures such as the Drive Section shrouds and nacelles shown in Figures 22 and 23 will be evaluated primarily in terms of fabrication costs because design loads are relatively low. Maximum usage of automated methods must therefore be made to minimize the labor costs of fabrication. Because of the large amount of repetition in this structure, an obvious labor-saving technique is precasting. In conjunction with the use of precasting molds, automated methods for forming reinforcement, placing, compacting and finishing mortar, and curing should lead to greater economy. Further development of automated methods, if necessary, should be within the scope of a project of the magnitude of the proposed wind tunnel.

Additional cost factors related to the use of ferro-cement for wind tunnel construction include research and development to establish and verify optimal ferro-cement parameters for the proposed usage, cost of production facilities such as molds, placing and curing equipment, and erection of precast ferro-cement segments. Most of the factors related to erection are within the present state-of-the-art in precast and pre-stressed concrete construction.

A detailed cost estimate was prepared for the Drive Section in Figures 22 and 23 based on recommendations made by David J. Seymour, Naval Architect, which are included in Appendix B. These recommendations were based on detailed, specialized knowledge (much of it proprietary) gained by Mr. Seymour in conjunction with a research and prototype-

construction project for development of ferro-cement for large sea-going cargo barges.^{4,34} Mr. Seymour's responsibilities relative to this work included complete design, production of working drawings for the prototype barge, and construction planning.

The estimated unit costs for the Drive Section shown in Figures 22 and 23, listed in Table VII are based on those presented in Appendix B.

TABLE VII
ESTIMATED FERRO-CEMENT UNIT COSTS FOR
WIND TUNNEL DRIVE SECTION

<u>Item</u>	<u>Unit Cost/ Square Foot</u>
1. Research, development, design & engineering	\$0.17
2. Molds	0.24
3. Fabrication	4.50
4. Assembly	0.67
5. Contingencies 15%	0.83
TOTAL	\$6.41

The principal item subject to variation in this summary is Item 3, the cost of materials and labor in fabricating ferro-cement segments. Lower costs would be expected for structures with lower operational loads and dimensional tolerance requirements. Further development of automated fabrication methods and equipment would be expected to further reduce this figure. Fabrication and assembly of ferro-cement for flat surfaces would also be expected to have lower unit costs than given in Table VII. It should be noted, however, that other building materials, such as rolled-steel plate, would likewise be less expensive for flat areas.

The costs shown in Table VII are based on ferro-cement shrouds and nacelles that are completely supported by structural steel framing spaced on 20-foot centers. It is possible that design optimization for load-carrying capacity of both steel framing and ferro-cement could lead to some reduction of overall construction costs. This would require optimization of such factors as ferro-cement shell thickness, concrete rib spacing and prestressing, and structural steel framing size and spacing.

The ferro-cement unit cost in Table VII has been used to revise the cost of Concept III (Ferro-cement) contained in Table A of John A. Blume & Associates, Engineers report "Conceptual Design Study of Power Section for Proposed V/STOL Wind Tunnel," dated March 22, 1971. That report contains a comparison of four cost estimates for a Power (Drive) Section with shrouds and nacelles of structural steel, pre-cast concrete, ferro-cement, and reinforced plastic. The updated cost estimate for the ferro-cement concept is included in Appendix D of this report.

VII. SUMMARY OF FINDINGS

The principal findings of the state-of-the-art study, testing program, and cost study are summarized below.

A. STATE-OF-THE-ART STUDY

1. Ferro-cement is a relatively new structural material that consists of a thin-shell of Portland cement mortar reinforced with large amounts of steel wire. Its unique material properties, which mainly result from a large bond surface area between the steel and mortar (specific surface of reinforcement), include increased tensile stress at formation of tension cracks and improved cracking behavior relative to unreinforced mortar and reinforced concrete.
2. Ferro-cement as a structural material can be engineered to a relatively high degree of precision, yet utilizes low cost materials and can be adapted to relatively low cost production methods. In this regard it has been successfully used for several decades in construction of marine craft.
3. Ultimate compressive strength of ferro-cement is determined primarily by the strength of the mortar matrix. Typical ferro-cement mortars utilize a high quality fine aggregate with high cement and low water content, and have high ultimate strength.
4. Under tensile and flexural loading, increased stress at formation of the first mortar cracks and decreased crack width are directly related to increased specific surface of reinforcement. The stress range preceding formation of first crack is defined as the effective elastic range of the material. Ultimate ferro-cement

capacity is directly related to reinforcement capacity for tension and flexure.

5. Ferro-cement shear capacity is relatively low; the use of reinforcing bars appears to increase shear strength.
6. Modulus of elasticity is related to volume of reinforcement and decreases after formation of cracks.
7. Based on fabrication and finishing methods for reinforced concrete, a wide range of surface textures is achievable. Wear resistance of ferro-cement surfaces is primarily related to mortar strength, finishing, and curing methods.
8. Corrosion resistance of uncoated ferro-cement shells is determined by quality and permeability of mortar, thickness of reinforcement cover, presence of cracks, and crack width. Quality and density of mortar and cracking behavior favor corrosion resistance, but thin ferro-cement reinforcement cover is generally detrimental. Use of a polymer latex additive gel-coat appears to be an ideal way of improving corrosion resistance.
9. Based on approximate design methods, 5/8-inch and 1-inch ferro-cement (approximated by dense concrete) can be expected to give greater acoustical attenuation than 1/8-inch and 3/8-inch steel plate, respectively, for some portions of the sound-frequency range.
10. Yielding of ferro-cement under repeated flexural loading is related to the fatigue behavior of the steel reinforcement.
11. Resistance of ferro-cement to fire is relatively high.
12. Impact resistance of ferro-cement increases with increased specific surface and tensile strength of reinforcement.

Comparatively speaking, impact resistance of equal thicknesses of marine plywood and ferro-cement are approximately the same, while impact resistance of fiber reinforced plastic is greatly superior to ferro-cement. Impact resistance of ferro-cement can be increased significantly with an overlay of fiber reinforced plastic. Relatively low ferro-cement impact resistance is partially offset by the ease of repair of damaged areas.

13. Currently used ferro-cement fabrication techniques consist of (a) manual construction of reinforcement network combined with manual lay-up and finishing of mortar, and (b) various automated procedures such as spray application of mortar, layering build-up of mortar and mesh, mechanized dispensing of mortar and vibration, all which are related to the use of molds.

B. TEST PROGRAM

1. The results of static compression, tension, and flexural tests of ferro-cement laboratory samples compared well with results for similar samples by other investigators.
2. Based on results of static tests, the static design load capacity of a 1-1/8-inch ferro-cement section is estimated to be comparable in compression and flexure to a 1/4-inch unstiffened structural steel plate of approximately equal weight. Flexural rigidity of the ferro-cement section is estimated to be much greater than that of the steel section.
3. The formation of the first crack in ferro-cement test samples during flexural fatigue loading (to a maximum of 1,000,000 cycles) was found to be difficult to determine. Fatigue loading was in one direction only; four test samples were uncracked and seven were cracked prior to fatigue testing. Measurements of load-deflection behavior were made periodically during fatigue loading.

of test samples. Evaluation of the effects of fatigue loading to a maximum stress of from 52 percent to 170 percent of estimated cracking stress, based on the load-deflection measurements, indicates no significant fatigue deterioration of the samples occurred within the range of the tests.

4. Flexural vibration records of ferro-cement samples indicated variation in the internal damping ratio for the cracked and uncracked conditions (average values of 4.3 percent and 3.0 percent, respectively). Computed values of dynamic modulus of elasticity based on observed frequencies of free vibration indicate a similar variation. The average values for cracked sections and uncracked sections were 3,400,000 psi and 5,250,000 psi, respectively. These values compare very well with measurements of modulus of elasticity obtained from static tests.
5. Qualitative evaluation of air abrasion tests, wherein two test samples were subjected to high velocity air flow which exerted a pressure of 6 psi over a 4-square-inch area for a period of seven days indicates that the surfaces of the samples were not affected by the test.

C. COST STUDY

1. There are no completed ferro-cement structures similar to a large-scale, subsonic wind tunnel Drive Section from which to directly obtain cost data.
2. The most significant cost factor related to ferro-cement construction is the labor involved in manufacturing the ferro-cement. This is the area where most cost reductions can be made through the use of automated fabrication methods.

3. Based on discussions and evaluation by consultants experienced in design and fabrication of ferro-cement marine construction, unit costs for ferro-cement Drive Section shrouds and nacelles of the type described herein are estimated at \$6.41 per square foot for a 5/8-inch thick ribbed shell supported by structural steel framing.

VIII. CONCLUSIONS AND RECOMMENDATIONS

A number of conclusions were reached as a result of the study and evaluation described in this report relative to the general structural use of ferro-cement and more specifically to its use for wind tunnel construction. The need for additional research studies into some ferro-cement material properties was also recognized and a number of recommendations were made. These conclusions and recommendations are listed in the following sections.

A. CONCLUSIONS

The principal conclusions relative to the use of ferro-cement for wind tunnels are the following:

1. The current state-of-the-art favors the applicability of ferro-cement to some parts of wind tunnel construction. However, further experimental studies are needed to bring the state-of-the-art up to the standards of other structural materials, such as steel and reinforced concrete.
2. Because some ferro-cement strength properties are low relative to other wind tunnel construction materials, such as structural steel, it cannot be used in all types of structures. However, in many structures where ferro-cement load capacity is compatible with structure design loads, significant cost advantages can be expected over structural steel.
3. For many applications, ferro-cement structures can be expected to require very little or no regular maintenance. But, because of the thinness of the sections and the thin steel coverage,

high quality materials and workmanship will be required for good strength properties and durability.

4. Relative to structural steel, ferro-cement can be used most advantageously in thin-shell construction having single or compound curvature because the curvature will result in increased rigidity and decreased stresses. Ferro-cement also can be formed in curved shapes with relatively little cost increase over flat surfaces, while rolled steel plate production is much more expensive, especially in compound curvature.
5. Present ferro-cement construction is labor intensive, thus economical production on a large-scale basis is dependent on labor-saving automated fabrication methods. The use of molds for precasting, and automated mortar placing and curing procedures are advantageous for structures with a large degree of repetition.

B. RECOMMENDATIONS

The results from the state-of-the-art study of ferro-cement material properties, construction methods, and a preliminary testing program show that ferro-cement appears to be quite feasible for some types of wind tunnel construction. However, the need for further investigation into some physical properties of ferro-cement and ferro-cement structures is indicated. The recommendations for further ferro-cement studies discussed in Chapters III through VI with special reference to wind tunnel construction are summarized below.

Design and construction of some ferro-cement structures can be based on the current state of knowledge, as have many marine craft and some civil engineering structures. However, for important or unusual new structures, such as wind tunnels, appropriate studies from additional tests outlined below are recommended.

1. Fatigue Testing: Additional fatigue tests to better relate cracking behavior and crack width to fatigue loading. Parameters such as number of cycles, frequency and amplitude of loading, volume and specific surface of reinforcement and load range should be studied.
2. Full-scale Mock-up Tests: Load testing of full-scale or large-scale structural elements, such as precast shroud and nacelle segments for a subsonic wind tunnel Drive Section. Load testing of sub-assemblies such as joints, connections, and seals.
3. Reinforcement Study: Determine optimum reinforcement for given structural applications as a function of size, strength, spacing, specific surface and economy. Evaluate behavior of mortar-reinforcement matrix during cracking, yielding and failure.
4. Mix Design Study: Detailed study for optimizing mortar mix design. Determine the effect of type of cement and aggregates, mix proportions, and curing methods on ferro-cement parameters such as compressive strength, durability, shrinkage and economy.
5. Durability: Evaluate significance of various material parameters for improving durability of ferro-cement in wind tunnel environments. Determine necessity of protective coatings for various applications. Evaluate economy of different forms of corrosion protection.
6. Acoustical Attenuation: Evaluate the effects on acoustical absorption and sound transmission-loss of variables such as ferro-cement density, structural details, and cracking. Study methods for improving acoustical characteristics.
7. Fire Resistance: Establish fire rating for ferro-cement.

8. Impact Resistance: Develop tests to simulate anticipated impact loads on specific structures. Evaluate the adequacy of the ferrocement sections designed for these structures, and study methods for improving impact strength, where required.

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APPENDIX A

PRELIMINARY CRITERIA FOR DESIGN OF FERRO-CEMENT SHELLS

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PRELIMINARY CRITERIA FOR DESIGN OF FERRO-CEMENT SHELLS

The following preliminary criteria for design of ferro-cement structures are based on an evaluation of a state-of-the-art survey, current design and construction practices, and the results of a limited testing program. These criteria are specifically related to wind tunnel structures such as the proposed large-scale, subsonic wind tunnel Drive Section. More extensive testing as discussed in Chapter IX of this report will be required to establish final criteria for structural use of ferro-cement.

A. Loads

1. Vertical Loads:

- a. Dead load of ferro-cement shell and ribs.
- b. Floor live load (Uniform Building Code, 1970 Edition, Table No. 23-A).
- c. Roof live load (Uniform Building Code, 1970 Edition, Table No. 23-B) -- 20 psf basic.

2. Lateral Loads:

- a. External wind loads in accordance with UBC (Section 2308).
- b. Seismic loads should be in accordance with the appropriate spectral acceleration curves corresponding to the maximum probable earthquake that should be determined for the site. The dynamic response of ferro-cement structures to seismic motion should be considered in final design. This state-of-the-art procedure is now used in the design of major facilities throughout the United States such as nuclear power plants and large office buildings. It provides a better picture of the response of structures and equipment to possible earthquake motions and hence enables the engineer to more efficiently design the facilities to resist seismic motions. Structural elements should be designed with increased allowable stresses for resisting the maximum seismic loading. It is recommended that a detailed study be made to develop final seismic design criteria before construction designs are initiated.

3. Operational loads as required for specific structure. A typical operational pressure diagram based on recommendations of NASA Ames Research Center personnel for a large-scale, sub-sonic wind tunnel is shown in Figure A-1.

B. Design Standards

1. Mortar: Mix design considerations shall be based on current state-of-the-art for ferro-cement and applicable specifications of the ACI Code (ACI-318-72). Acceptable standards for mortar mix materials and design are:
 - a. Aggregate shall be in accordance with ASTM C 33 for fine aggregate or ASTM C 330 for lightweight fine aggregate. In general, aggregates must be of the highest quality and free of deleterious substances. When tested in accordance with ASTM C 40, the material should be essentially free of organic impurities. Grading of aggregate should be such that 100% passes a No. 8 sieve and should, in general, provide a mortar with high density and good workability.
 - b. Cement shall conform to ASTM C 150.
 - c. Grading of aggregate and ratio of aggregate-to-cement shall be carefully controlled to provide uniform properties throughout the structure. Control of fineness modulus shall conform to ASTM C 33 or C 330. Similarly, water-to-cement ratio shall be carefully controlled. The specified mix proportions should be maintained through careful control of batching operations and unit weight of mortar. Compression tests at 1-, 7- and 28-day curing periods shall be taken to check uniformity.
 - d. Admixtures used shall conform to Federal Specification SS-P-570b and ASTM Standards C 260, C 494 or C 618. Entrapped air should be measured and kept to a minimum. The use of additives not covered by the above specifications, such as polymer latex additives, shall be based on test data to verify compliance with specified mortar characteristics.
 - e. Workability of mortar, as established by grading, cement content, water content and additives, shall be consistent with obtaining the highest quality ferro-cement construction.

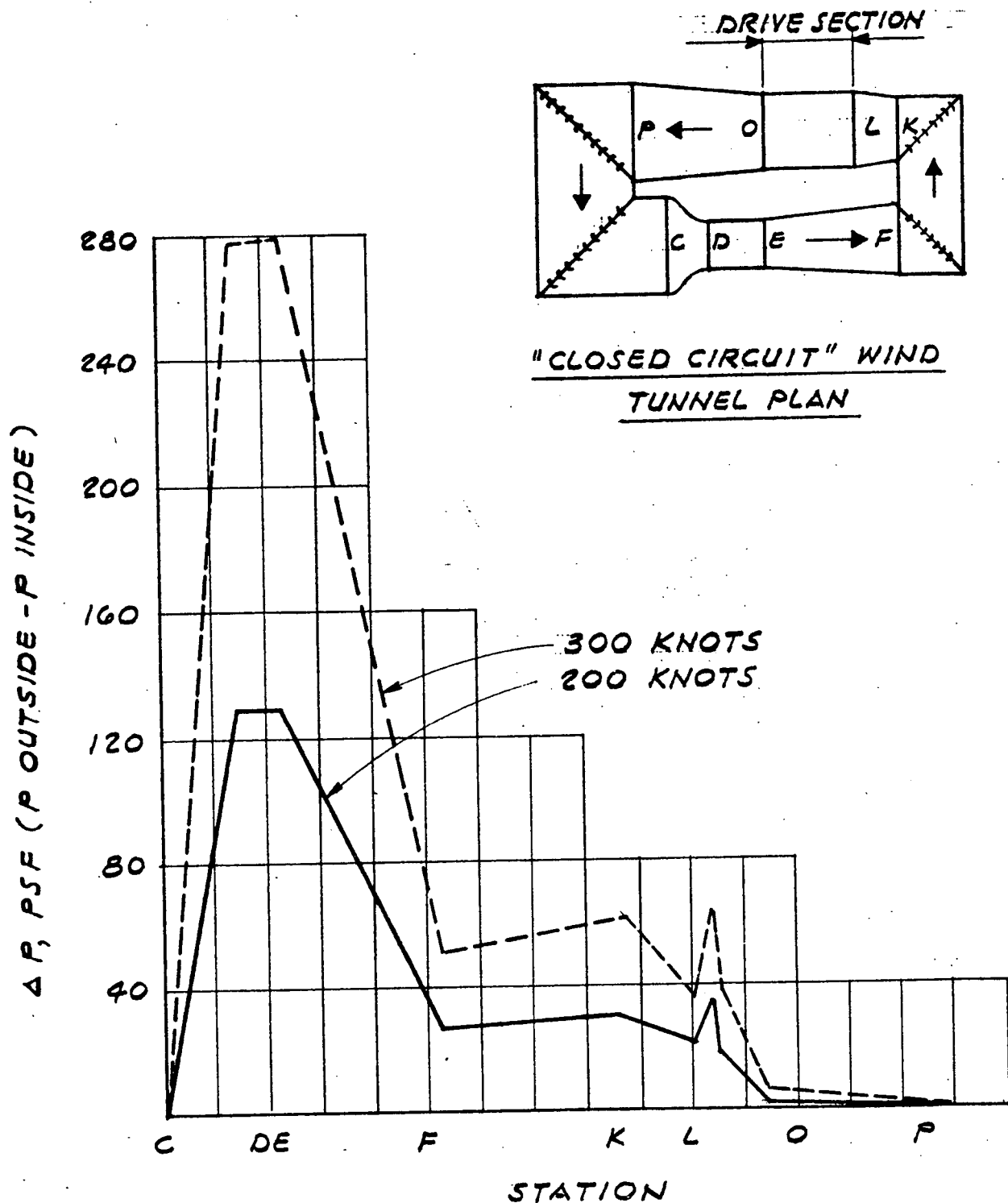


FIGURE A-1 - TYPICAL PRESSURE DISTRIBUTION FOR LARGE-SCALE SUBSONIC WIND TUNNEL

- f. Aggregate selection and mix design should minimize drying shrinkage, which should be less than 0.03 percent for laboratory control samples, as determined by ASTM C 341.

2. Reinforcing Steel:

- a. Wire mesh shall be welded wire mesh or woven wire mesh conforming to ASTM A 185. Wire shall conform to ASTM A 82.

- b. Reinforcing bars shall be as specified by ASTM A 615 or ASTM A 616 for Grade 60.

3. Surface Cracking: Extent of surface cracking and maximum crack width allowed shall be as permitted for specific structural application.

4. Ferro-cement Design Stresses: Design stresses should be based on consideration of the material as an equivalent homogeneous cross section. Design values are dependent on the type and configuration of materials (mortar and reinforcing) used and are defined by the current research results representing the state-of-the-art in ferro-cement, which are discussed in Chapter III of this report. Design stress for a specific cross section should be as follows, where F.S. represents an appropriate factor of safety:

- a. No cracking allowed:

$$\text{Design stress} = \frac{\text{First cracking stress}}{\text{F.S.}}$$

- b. Cracking permitted:

$$\text{Design stress} = \frac{\text{Ultimate stress}}{\text{F.S.}}$$

Design stress as related to allowable crack width is currently under study. See Chapter III of this report.

The value of F.S. is based on the intended structural use and type of loading, ferro-cement research results and the principles

of reinforced concrete design. For simplicity, a factor of safety was used for determining design stress. It should be noted, however, for reinforced concrete design the value of design stress is based on statistical considerations and on keeping within a maximum probability (generally extremely small) of failure.

5. Structural Support: Supports and connections for ferro-cement structures shall be capable of resisting all loads on the structure. These shall conform to current design practice and be verified by load tests.

C. Fabrication Standards

1. Dimensional Tolerance: Fabrication and erection procedures shall ensure structural tolerances as required.
2. Surface Quality: Surface texture shall be as required in finished structure. Design and fabrication methods shall ensure adequate surface quality for a specified service life.
3. Durability and Corrosion Resistance: Ferro-cement design and fabrication shall ensure durability of the material. Careful consideration shall be given to mortar corrosion resistance and permeability, reinforcement, and placing and curing methods. Galvanized reinforcement shall be used whenever possible. Adequacy of the design or the need for protective coatings shall be established by appropriate tests for each structure.

APPENDIX B

REVIEW OF FEASIBILITY OF USING FERRO-CEMENT CONSTRUCTION

FOR PROPOSED NASA WIND TUNNEL DRIVE SECTION

APPENDIX B

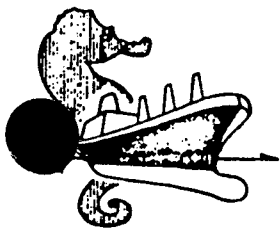
REVIEW OF FEASIBILITY OF USING FERRO-CEMENT

CONSTRUCTION FOR PROPOSED NASA WIND TUNNEL

DRIVE SECTION

The following report prepared by David J. Seymour of David J. Seymour, Naval Architects and Marine Consultants, contains a feasibility review and cost estimate for the proposed use of ferro-cement in wind tunnel construction. This work is based on Mr. Seymour's experience with the design and construction of a large ferro-cement cargo barge which is discussed in the preceding text.

The wind tunnel structure on which the ferro-cement cost estimate in this appendix is based is the Drive Section shown in Figures 22 and 23 of the preceding text. This structure contains 20 drive units (4 high by 5 wide) and is 200 feet long. The ferro-cement portions are the shrouds and nacelles which provide aerodynamic surfaces for the flow of air past the drive unit fans. Total surface area of these ferro-cement shrouds and nacelles is approximately 900,000 square feet. The cost estimate developed by Mr. Seymour is given in terms of both total cost for 900,000 square feet and unit cost on a square foot basis. Using the unit cost, estimates can be made of the ferro-cement costs for similar structures.



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April 13, 1972
File 212

John A. Blume & Associates, Engineers
Sheraton Palace Hotel
100 Jessie Street
San Francisco, California 94105

Attention: Mr. Roland L. Sharpe, Executive Vice President

SUBJECT: FEASIBILITY REVIEW OF FERRO-CEMENT FOR
PROPOSED NASA WIND TUNNEL

Encl. 1) DJS SK. 212 - Ferro-Cement Design for Wind
Tunnel

Gentlemen:

In accordance with your request, I have completed a general feasibility review of the utilization of ferro-cement panels for lining of the surface areas of shrouds and nacelles in the drive section of subject wind tunnel.

The objectives of my review were primarily to:

- a) Consider general design, fabrication and assembly methods of ferro-cement for this application.
- b) Estimate unit costs based on designs of item a) above.
- c) Determine the engineering feasibility of employing ferro-cement in relation to the current "state of the art" for this material.

1. DESIGN, FABRICATION & ASSEMBLY METHODS

- a) Data and design criteria used in this review:
(as given by Blume Engineers)

April 13, 1972

SHROUDS - Dia. (max.) 48 ft., Dia. (min.) 40 ft.,
length 200 ft.

NACELLES - Dia. (max.) 20 ft., (min.) 2 ft.,
length 200 ft.

No. of SHROUD/NACELLE UNITS - up to 20 (4 high -
5 across).

Height to top shroud above ground - about 210 ft.

Air Pressure Loading - Shrouds 100 PSF, Nacelles
0 PSF.

Surface Tolerances - Offsets from Fan

0 - 20 ft. = 0 in.

20 - 30 ft. = +3/32 in.

Over 40 ft. = + 1/2 in.

Steel Supporting Structure - in place for shrouds
with support points at 20 ft. intervals.

b) General Design Considerations

The design criteria for present ferro-cement construction, primarily in marine application, have been based on strengths to meet hydrostatic loading (up to 700 PSF), stresses due to hogging and sagging bending moments, water tightness, impact damage, fire and corrosion resistance. These are not present in the requirements for subject wind tunnel. However, two new design parameters have been added, namely fan induced vibration loading and wind erosion. Little data is available on these factors for ferro-cement and, although not considered a major problem area, it is recommended that some R&D effort be directed to determine their effects.

Due to repetitive compound shapes involved, requirements for accuracy in surface tolerances and, inaccessibility for efficient "in place" fabrication, the precast method is the obvious solution. Precasting would permit accurate surface shape control

(side against mold), precision forming of joint edges and, fabrication under quality control conditions.

Optimum panel size should be based on unit weight and costs, to provide suitable panel strength for self-supporting, ease of transportability to site, and for efficient assembly operations.

The latter will most probably control panel size and weight because of the height of shrouds above ground and the interference of pre-installed steel structure.

c) Review of Precast Method

Shroud panels should be easily fabricated by employing a male mold representing the full length of $1/2$ of the diameter of a shroud. Panels should be cast in 20 ft. lengths to match structure support points and be $1/8$ or $1/4$ circle sections. Precast ribs and stiffening member would be cast into panel when latter is poured. See Sketch Encl. 1).

Nacelle panels should similarly lend themselves to construction but on a female mold. Due to their 20 ft. diameter, it appears feasible that internal framing of ferro-cement material could reduce considerable amount of nacelle steel support structure. Consideration might be given to eliminating all nacelle steel structure by introducing a prestress (post-tension) system to accommodate the spans between struts. See Sketch Encl. 1).

In employing the precasting method, only one mold for shrouds and one for nacelles would be required. Accurate surface dimension control of the compound curves would be insured being faced on the mold. Finishing and application of coatings would be done prior to assembling panels in place.

d) Ferro-Cement Panel Design

Although a wide variety of lay-up materials, configurations and cement mortar may be suitable for

April 13, 1972

this application, the writer has selected a panel design based on the most advanced developments in marine design. Considerable research data and actual construction, including approval by marine regulatory bodies, are incorporated in its design so that it should be a sound basis for cost and feasibility evaluation.

Principal Characteristics of Panel

Thickness - 5/8" overall

Lay-Up - 1 layer WWM 1/4" x 1/4" x 21 ga. (S_y 80,000 psi)
1 layer Rod 1/4" dia. on 2" centers (S_y 80,000 psi)
2 layer WWM 1/4" x 1/4" x 21 ga. (S_y 80,000 psi)

Stiffner Spacing - 4 ft.

Cement Mortar - Lightweight Cement, Crushed and Uncrushed Saturnlite Sand, Pozzolan and Pozzoloth and Special Additives.
Slump - 0

Vibrators - extensive use of vibrators on mold and hand type to insure full penetration

Curing - accelerated at low temperature

See Sketch Encl. 1)

e) Assembly Methods

In the writer's opinion, the assembly method will be a major factor affecting the feasibility of using ferro-cement for this project.

The controlling factors for optimum panel size and weight would be for ease of handling, positioning, alignment and securing. Also unit cost per sq. ft. and joint length would be reflected in optimizing.

The following method was selected for analysis:
(assume nacelle steel work to be installed after shroud panels are in place)

- i) Transfer 20 ft. long precast and prefinished shroud panels by hoisting to shroud level.
- ii) Transfer panel into position within shroud by special dolly, track and jig.
- iii) Set panel in place and align with Laser.
- iv) Epoxy, grind and finish joints - touch up as required.
- v) Install steel struts and nacelle steel framing.
- vi) Install 20 ft. nacelle panels similar to steps for shroud.

2. COST ESTIMATE

The following assumptions were included in preparing cost estimate.

Total Ferro-Cement Panel Area - approx. 900,000 sq. ft.
(includes area of concrete drive unit support - 20 units)

Allowance for R&D, Design and Engineering.

Material and Labor for Molds.

Material and Labor for Manufacturing.

Material, Equipment and Labor for Assembly - hoists, jigs, dollies, staging, etc.

Contingencies (margin, changes, escalation, etc.) of 15%.

SUMMARY

	<u>\$ TOTAL</u>	<u>UNIT\$/Sq.Ft.</u>
A. R&D, Design & Engrg.	150,000	0.17
B. Molds	215,000	0.24
C. Manufacturing	4,050,000	4.50
D. Assembly	<u>600,000</u>	<u>0.67</u>
	5,015,000	
E. Contingencies 15%	<u>752,000</u>	<u>0.83</u>
TOTAL	<u><u>5,767,000</u></u>	<u><u>6.41</u></u>

April 13, 1972

3. FEASIBILITY

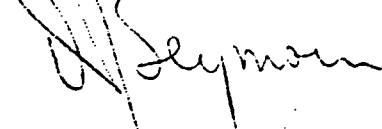
In the writer's opinion, the concept of employing ferro-cement material for lining of the shroud and nacelle surfaces is feasible from both a construction and economic viewpoint.

The proposed application here of ferro-cement is well within the current "state of the art" of the material. This is further supported by the fact that it is exposed to less severe environment and loads than those found in marine practice.

Also rapid developments are presently underway, by commercial and governmental agencies, in the research and application of this material to improve both its strength and weight characteristics. These improvements no doubt will be available to incorporate in this project.

In addition, due to the large areas of ferro-cement involved, efforts can be afforded in optimization of design, fabrication and assembly methods to produce improvements over the writer's assumptions used in this evaluation.

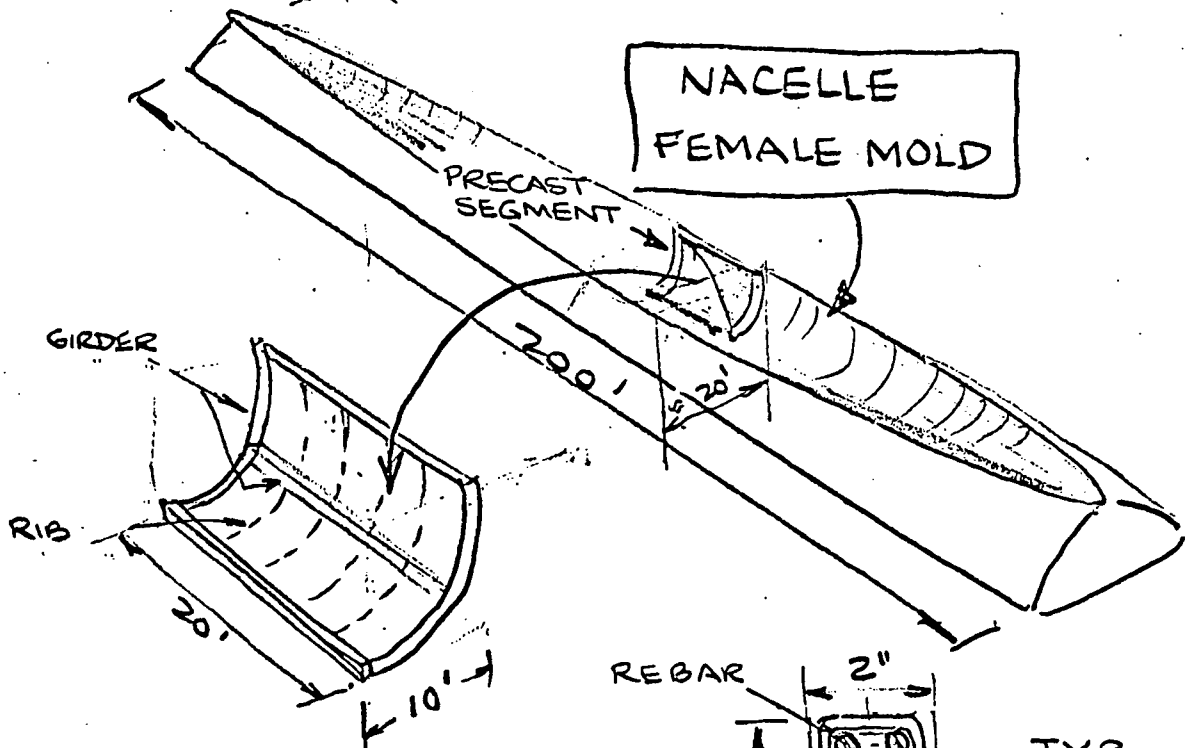
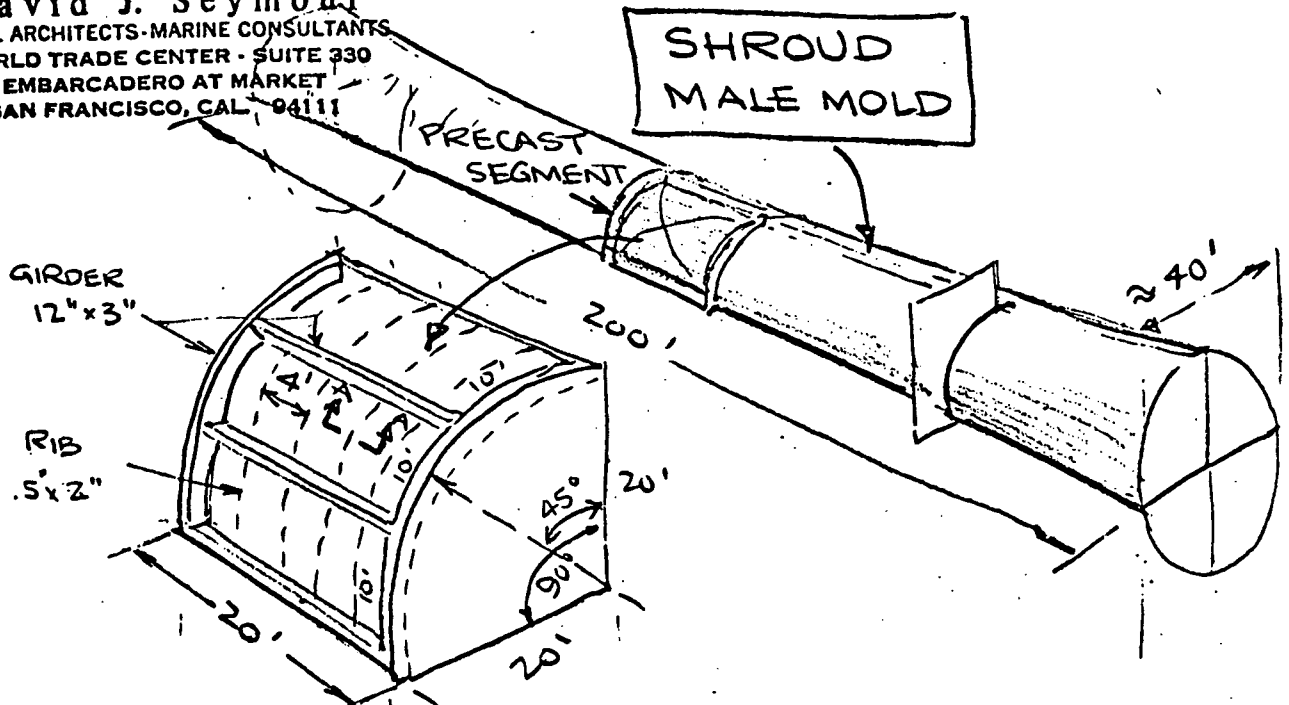
Very truly yours,

A handwritten signature in dark ink, appearing to read "D. Seymour", written over a horizontal line.

DAVID J. SEYMOUR

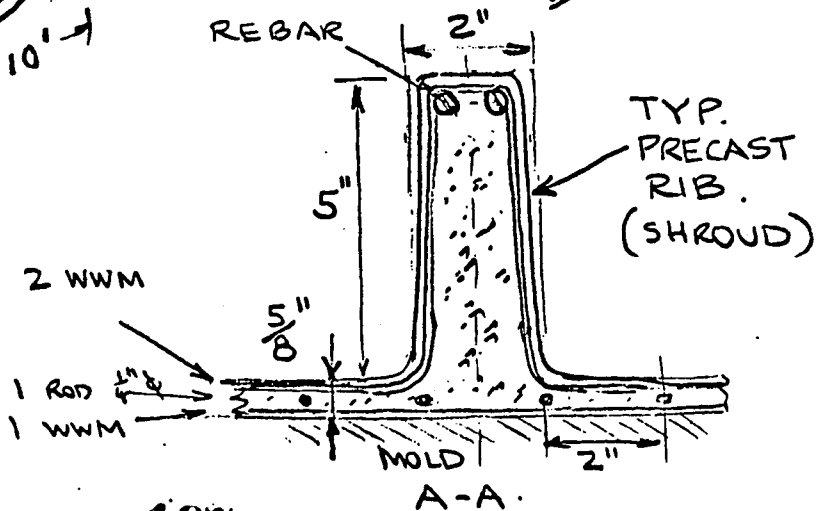
DJS/rb

David J. Seymour
 NAVAL ARCHITECTS-MARINE CONSULTANTS
 WORLD TRADE CENTER - SUITE 330
 EMBARCADERO AT MARKET
 SAN FRANCISCO, CAL. 94111



APPROX WEIGHTS
PANEL SEGMENTS

SHROUD @ 16.0 #/sq ft = 9600 #
 NACELLE @ 12.0 #/sq ft = 3600 #



FERRO-CEMENT
 DESIGN FOR
 WIND TUNNEL

APPENDIX C

LABORATORY REPORT ON STRUCTURAL INVESTIGATION OF
FERRO-CEMENT SPECIMENS

SAN JOSÉ STATE COLLEGE

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SCHOOL OF ENGINEERING
Department of Civil Engineering
and Applied Mechanics

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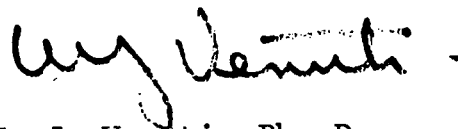
Mr. Roland L. Sharpe
Executive Vice President
John A. Blume & Associates, Engineers
100 Jessie Street
San Francisco, California 94105

Dear Mr. Sharpe:

Enclosed are three copies of the Laboratory
Report on Structural Investigation of Ferro-Cement
Specimens.

Please inform me if you wish to discuss
the report in more detail. It has been a pleasure
to be of service to your firm.

Very truly yours,



W. J. Venuti, Ph. D.
Professor of Civil Engineering

LABORATORY REPORT
on
STRUCTURAL INVESTIGATION OF
FERRO-CEMENT SPECIMENS

for
John A. Blume & Associates, Engineers
100 Jessie Street
San Francisco, California 94105

by
William J. Venuti, Ph. D.
Department of Civil Engineering
and
Applied Mechanics
School of Engineering
California State University, San Jose
San Jose, California 95114

June 1972

STRUCTURAL INVESTIGATION OF FERRO-CEMENT SPECIMENS

Introduction

John A. Blume & Associates of San Francisco, California, has engaged in a preliminary study of the static, dynamic, and fatigue characteristics of ferro-cement as a structural material. The Department of Civil Engineering and Applied Mechanics of the California State University, San Jose, has collaborated with John A. Blume & Associates in conducting the experimental phase of the study.

This report presents an account of the experimental design and description of the laboratory equipment utilized in conducting the experimental study. A description of the ferro-cement mix design and reinforcement, laboratory data, and analysis of the data is presented separately by John A. Blume & Associates.

Laboratory Tests

The following tests were conducted on the ferro-cement panels and specimens:

1. Flexural static tests
2. Flexural fatigue tests
3. Flexural vibration tests
4. Beam shear tests
5. Cube compressive tests
6. Slab compressive tests
7. Wire mesh strand tensile tests
8. Slab tensile tests
9. Air Flow tests

The following sections describe the specimens tested, laboratory equipment, instrumentation and method of loading of the various tests.

The entire laboratory study was conducted in the Advanced Structures Laboratory of the California State University, San Jose.

All load indicator systems used in this experimental program are calibrated and certified to be traceable to the U.S. Bureau of Standards.

FLEXURAL STATIC TESTS

Specimen Preparation

Each flexural specimen was measured for thickness with a 0.001 inch accuracy micrometer. The measurements were taken at the corners of the zone of maximum bending moment.

At the bottom surface of the end of each flexural panel, quick setting mortar (Hydrocal) was placed in the vicinity of the support area. With the Hydrocal in a plastic state, the panel was slightly pressed against a rigid level table to obtain smooth and parallel surfaces of the beam end supports.

At the two loading points on the top surface of the beam, additional transverse strips of Hydrocal were placed. Prior to the setting of the Hydrocal, 1 inch wide by $\frac{1}{2}$ inch thick teflon pads were placed at the loading points. The pads having a length equal to the width of the beam, were pressed into the plastic Hydrocal with the channel loading device. This procedure assured uniform bearing of the loading device during testing.

Equipment and Instrumentation

The purpose of this series of tests was to determine the load-deflection relationship, cracking load, and ultimate load of each flexural specimen.

A 12,000 lb. capacity mechanical type Tinius-Olsen universal testing machine was used to apply the load. The 120 lb. loading range was used to obtain the load-deflection curve for the initial phase of each test. The 600 lb. loading range was used to carry the test to ultimate loading.

The beam end supports were free to rotate to eliminate longitudinal restraint of the beam. The load was applied at two points symmetrically located about the beam centerline. The load was applied by means of an aluminum channel which was accurately placed over the teflon strips. A spherical loading head attached to the upper platen of the testing machine applied the load to the loading channel.

Deflections were measured at the beam centerline with a Tinius-Olsen Model D-2 Deflectometer which incorporates a linear voltage differential transformer (LVDT). The deflection of the beam was magnified 100X and recorded on the machine 12 inch wide continuous chart recorder. The load-deflection curve was directly displayed on the recorder paper.

The loading rate for each test was set at 0.2 inch per minute.

In order to determine the load of the formation of the first flexural crack, silver conductive paint (with a butyl acetate base) was applied to the bottom surface near each outer edge along the length of the beam in the zone of maximum flexure. An electrical circuit was completed with a 3 volt ohmmeter. Upon the formation of the first flexural crack, the circuit breaks and the load at first crack is recorded.

FLEXURAL FATIGUE TESTS

Specimen Preparation

The specimens that were subjected to repeated loading in this series of tests were prepared in the same manner as those specimens used for the flexural static tests.

Equipment and Instrumentation

The purpose of this series of tests was to determine the number of cycles of repeated loading of specified magnitudes of load required to produce the formation of a flexural crack.

The same support and loading arrangement as used in the flexural static tests was used for these tests. However, the entire loading apparatus was contained in the loading frame of a 120,000 lb. Baldwin universal testing machine. The machine was used only for the purpose of positioning the loading head and specimens in a vertical direction.

The repeated loading was applied to the specimen by means of a hydraulic closed loop servo system. A 3000 pound capacity MTS hydraulic ram under load control was supported by the upper head of the testing machine.

The ram was actuated with an MTS servo-controller which received signals from a double bridge 500 pound capacity

electrical strain gage load cell. Hydraulic power supply was provided by a 10 gpm pumping unit. A micro-switch was placed beneath the ferro-cement specimen for the purpose of stopping the power supply in the event of panel failure during the application of the repeated loading. An LVDT was also placed beneath the center of the beam specimen to monitor centerline displacement at various times.

A Model 126B VCF/Sweep MTS Function Generator was used to supply the sinusoidal load input. The loading rate was maintained at 12 Hz. for all tests.

The magnitude of load and displacement were displayed on a Type 564 Textronix Storage dual beam oscilloscope with a Type 3C66 Carrier Amplifier and a Type 2B67 Time Base. The oscilloscope signals were channeled through a Model 297 Sanborn strip chart recorder.

To determine the number of cycles of repeated loading at which the first flexural crack occurred, a relay system was installed. The conductive paint circuit on the panel was connected to a relay which was placed in the circuit of an electric timer. The system was designed to break the circuit of the electric timer upon the formation of a gap in the paint circuit (caused by a flexural crack in the test panel). The number of cycles at first crack was determined by obtaining the product of the loading frequency and elapsed time.

FLEXURAL VIBRATION TESTS

Specimen Preparation

The three specimens that were tested for the purpose of obtaining the dynamic characteristics of the ferro-cement panels were prepared with Hydrocal at the support points and loading points similarly to those specimens used for the flexural static tests.

Equipment and Instrumentation

The purpose of this series of tests was to determine the fundamental flexural frequency of vibration and the damping coefficient for ferro-cement panels in a cracked and uncracked condition.

The same support and loading arrangement as previously described was used for this part of the testing program.

The testing procedure was as follows. The test panel was loaded downward statically to produce a positive moment corresponding to a predetermined load. The force of the loading ram was transmitted to the loading device on the test panel by means of a 12 inch length of $\frac{1}{4}$ inch diameter steel rod. The steel rod was then abruptly pulled away from the loading ram and loading device in order to excite the panel to vibrate at its natural frequency. In some cases, fixed

weights were placed on the loading device to prevent the panel from vibrating away from the end supports. In one case, weights were placed over the supports to assure that the beam maintained contact with the supports during vibration.

An LVDT placed beneath the centerline of the test panel was used to obtain the displacement variation with time. The displacement-time response was displayed on the oscilloscope with a persistent image of the beam. A photograph of the oscilloscope screen was taken with a Polaroid Land Oscilloscope camera.

The horizontal time rate of the oscilloscope beam was set at 0.2 sec. per cm. or 2 seconds for a full screen sweep of 10 cm.

The vertical scale of the beam was set at rates of .05 Volts, 0.1 Volts, 0.2 Volts, and 0.5 Volts/cm. The relationship between beam deflection and oscilloscope beam movement was established prior to the vibration tests.

BEAM SHEAR TESTS

The supports and loading points were prepared with Hydrocal as previously discussed. The load was applied in a hydraulic universal testing machine at a rate of 0.05 in./min.

CUBE COMPRESSIVE TESTS

The two-inch cubes of cement mortar were loaded in a hydraulic universal testing machine at a rate of 2000 psi/min. A spherical loading block was used to apply the load.

SLAB COMPRESSIVE TESTS

The loaded edges of the slab compression specimens were prepared with Hydrocal to assure uniform loading. A spherical loading block applied the load at a rate of 2000 psi/min. in a hydraulic universal testing machine.

WIRE MESH STRAND TENSILE TEST

Each length of wire was tested in tension in a hydraulic type universal testing machine. Each end of the wire was gripped in flat face wedge-type grips over a length of 3 inches. The free length of wire under tension was 12 inches. The rate of loading was approximately 50 lb./minute.

SLAB TENSILE TESTS

Each tensile specimen was prepared by applying a $3\frac{1}{2}$ inch length of Hydrocal to each face at each end. The

Hydrocal was placed in such a manner that the surfaces were smooth and parallel to each other. Conductive paint strips were vertically placed along each face near each vertical edge to determine the tensile load at first crack.

The specimens were subjected to a tensile force in a mechanical type universal testing machine. The flat face wedge type grips were shimmed to eliminate bending of the specimen under loading. The tensile force was applied at a rate of approximately 500 pounds per minute.

AIR FLOW TESTS

The purpose of these tests was to observe and examine potential structural deterioration resulting from a constant stream of air trained on the surface of a ferro-cement panel at a pressure of 6 psi. for a period of 7 days.

In this study, two panel surfaces were subjected to an air stream. One surface was the side of the panel that was adjacent to the form during construction and the other surface was one which was trowelled during the finishing operation.

An uncracked section of a 24 inch long beam was used for each test. The panel was placed in an upright position and fixed at an angle of 45 degrees to the air stream. A 2 in. by 2 in. square area of the panel surface was designated

as the test zone and placed so its center coincided with the center of the air stream.

The calibration of the apparatus was made as follows. One end of a $\frac{1}{2}$ inch diam. air hose was inserted into a hole in a $\frac{3}{4}$ in. thick wooden board and the opposite end of the hose was connected to a pressure gage. The board was then subjected to a steady jet of air which was issued from the valve of an 80 psi air supply line. The wooden board was positioned so that its surface was normal to the direction of the air stream. The opening in the panel where the hose was installed was centered on the air stream while pressure readings were taken. Based on readings of several trials, a pressure of 6 psi was obtained when the panel was placed at $3\frac{1}{2}$ inches from the face of the valve.

Using this relationship as a basis, the ferro-cement panels were also placed at a distance of $3\frac{1}{2}$ inches to obtain a pressure of 6 psi. The panels were rotated at 45 degrees to the air stream with the center of the test zone remaining at $3\frac{1}{2}$ inches from the valve.

The two panels were tested concurrently at different locations.

APPENDIX D

REVISION OF DESIGN STUDY OF POWER SECTION

FOR PROPOSED V/STOL WIND TUNNEL

APPENDIX D

REVISION OF DESIGN STUDY OF POWER SECTION FOR PROPOSED V/STOL WIND TUNNEL

The cost estimate for ferro-cement shrouds and nacelles, which was presented in Chapter VI and Appendix B of this report, was used to revise the cost estimate for Concept III (Ferro-cement) for the Drive (Power) Section that was the subject of the March 22, 1971, John A. Blume & Associates, Engineers report "Conceptual Design Study of Power Section for Proposed V/STOL Wind Tunnel."

A summary of revised cost figures for this Power Section is contained in Table D-1. This summary contains cost figures for the entire structure including structural steel framing, painting, piles, and concrete, including ferro-cement shells for shrouds and nacelles. The cost figures in Table D-I reflect the following basic revisions to the March 22, 1971, estimate:

1. Ferro-cement shrouds and nacelles are 5/8-inch shells with concrete stiffening ribs.
2. Ferro-cement is used throughout for shrouds and nacelles; no structural steel plate is used.
3. Slight increase in structural steel framing results from increased weight of revised ferro-cement shell and concrete ribs.

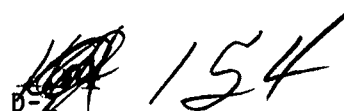
The unit price of \$6.41 per square foot for a 5/8-inch stiffened ferro-cement shell is based on the cost estimate in Appendix B. It should be noted that this unit price was developed for the revised Drive Section shown in Figures 22 and 23 of this report, which is 200 feet long with 20 drive units (4 high by 5 wide) containing approximately

TABLE D-I
REVISED COSTS FOR POWER SECTION STRUCTURE
(FERRO-CEMENT)

(Costs for Power Section 244 feet long containing 18 drive units,
described in the March 22, 1971, Blume report.)

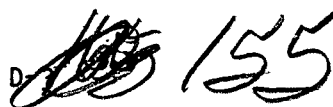
Description	Unit	Unit Cost	Number of Units	Cost for Total Units
<u>Piles</u>	EA	\$ 250.00	6,200	\$ 1,550,000
<u>Concrete</u>				
Pile caps	CY	85.00	13,200	1,222,000
Cast-in-place superstructure	CY	135.00	33,580	4,530,000
Ferro-cement shrouds	SF	6.41*	773,000	4,955,000
nacelles (including struts)	SF	6.41*	468,000	3,000,000
<u>Structural Steel</u>				
Shapes-Nacelles	T	1,000.00	3,680	3,680,000
Shapes-Shrouds	T	1,000.00	5,789	5,789,000
Shapes-Motor supports	T	1,000.00	771	771,000
<u>Painting</u>				
Shapes	SF	0.15	1,430,000	215,000
TOTAL COST				\$26,712,000

*Ferro-cement unit costs are based on cost estimate in Appendix B which is for a revised Power Section 200 feet long with 20 drive units and approximately 900,000 square feet of ferro-cement.

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900,000 square feet of ferro-cement. Although the Power Section discussed in the March 22, 1971, Blume report (and revised in Table D-1) is 244 feet long with 18 drive units and 1,241,000 square feet of ferro-cement, the loading conditions and construction problems are the same. Therefore, the unit cost of \$6.41 is applicable to both structures.

The revised costs in Table D-1 show an increase for the ferro-cement relative to the March 22, 1971, estimate. This increase reflects the more in-depth feasibility and cost studies contained in the present report and the revised construction recommendations. Based on conclusions reached in this report, the ferro-cement unit cost used in Table D-1 is conservative since advances in ferro-cement material research and design procedures and especially improvements in construction methods making greater use of automated fabrication techniques should lead to reductions in the estimated costs. Any reduction in fabrication cost will result in significant overall ferro-cement cost reduction because fabrication comprises over two-thirds of the total estimated ferro-cement costs.

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